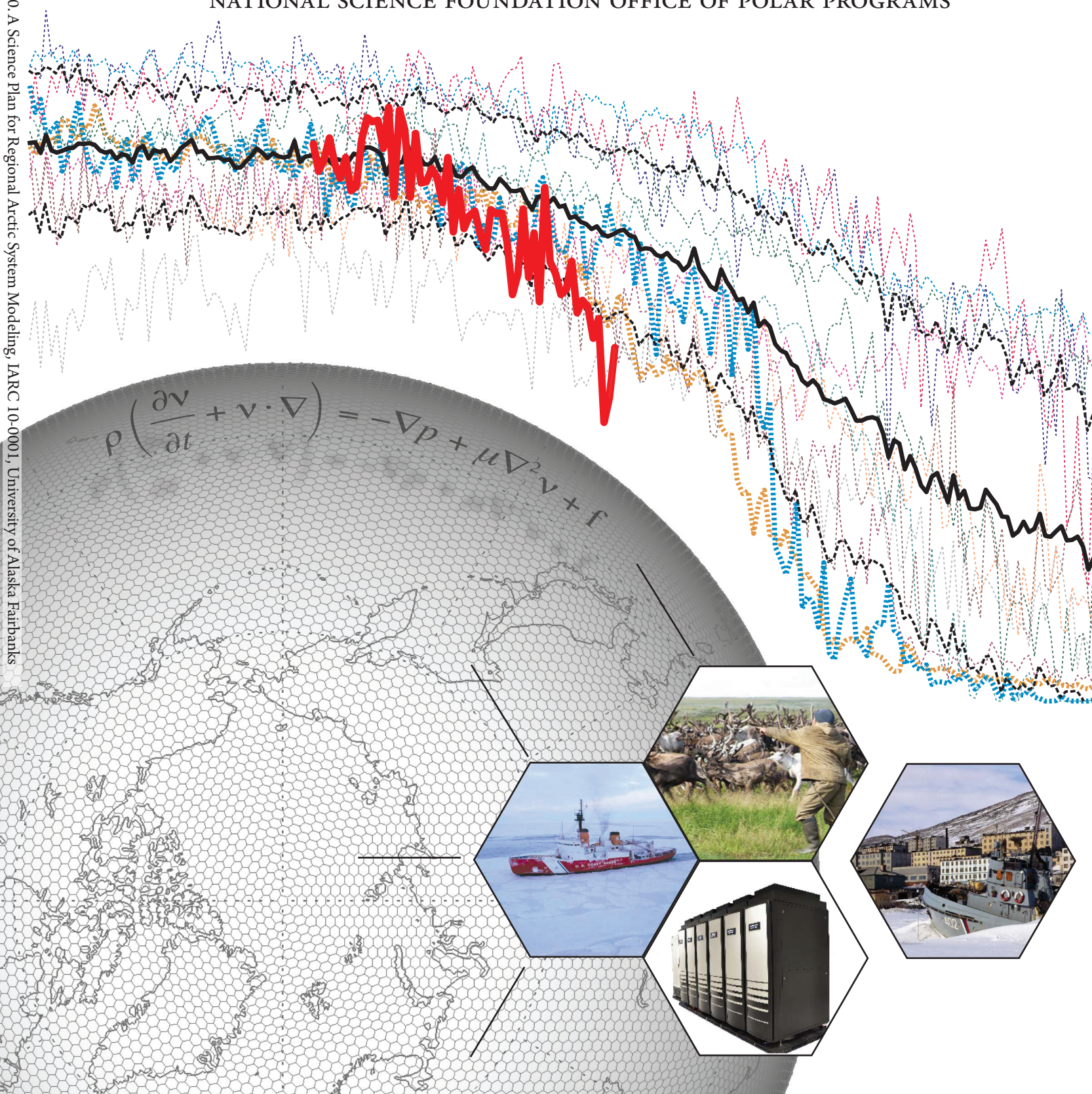


A SCIENCE PLAN FOR REGIONAL ARCTIC SYSTEM MODELING

A REPORT BY THE ARCTIC RESEARCH COMMUNITY
FOR THE
NATIONAL SCIENCE FOUNDATION OFFICE OF POLAR PROGRAMS



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Funding for this Report

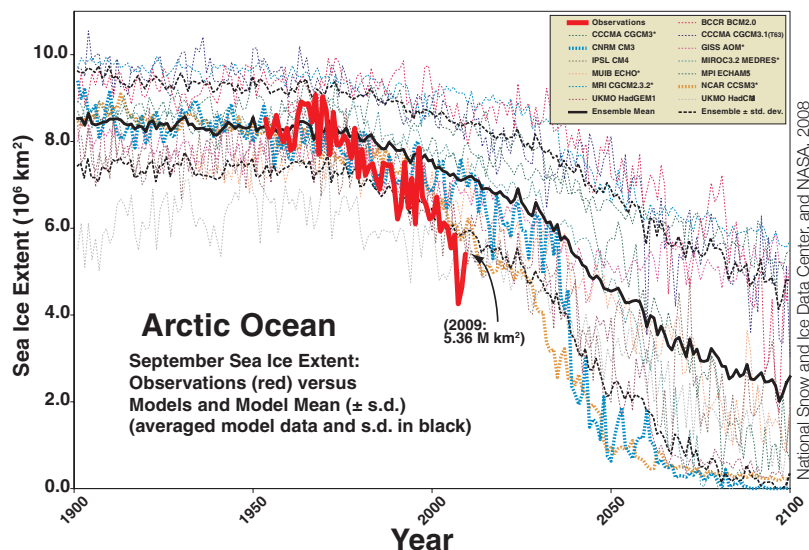
Primary funding for this effort was provided by the National Science Foundation Office of Polar Programs, Arctic System Science Program (OPP 0652838), and the Arctic Region Supercomputing Center. We are also grateful for support provided for one of three workshops that contributed to this report by SEARCH for DAMOCLES, the Canadian Foundation for Climate and Atmospheric Sciences, Centre pour l'étude et la simulation du climat à l'échelle régionale at the University of Quebec at Montreal, the Rossby Center at the Swedish Meteorological and Hydrologic Institute, and the International Arctic Science Committee.

Citation

This work should be cited as: Roberts, A. and coauthors 2010. A Science Plan for Regional Arctic System Modeling, A report to the National Science Foundation from the International Arctic Science Community. International Arctic Research Center Technical Papers 10-0001. International Arctic Research Center, University of Alaska Fairbanks.

An electronic copy of this publication is available at:
www.iarc.uaf.edu/publications/reports/IARCTP10-0001.pdf

Cover design by Russell Mitchell. Graph updated from Figure 1 of Stroeve et al. (2007) showing arctic September sea ice extent from observations (thick red line) and 13 IPCC AR4 climate models, together with the multi-model ensemble mean (solid black line) and standard deviation (dotted black line). The geodesic grid is one of many computational mesh configurations used for arctic modeling. The equation represents flow in an incompressible Stokes fluid, sometimes used to model hydrodynamics. Hexagonal insets, from left to right, are polar U.S. Coast Guard operations, reindeer herding, a Cray XT5 computer (courtesy of Mary Haley, Arctic Region Supercomputing Center), and the Russian port of Provideniya, in the Bering Strait.



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EXECUTIVE SUMMARY

The Arctic is experiencing changes never before seen in historic times. The physical, chemical, biological, and social components of the Arctic System are interrelated, and therefore a holistic perspective is needed to understand and quantify their connections and predict future system changes. A regional Arctic System Model (ASM) will strengthen our understanding of these components. It will advance scientific investigations and provide a framework for improving predictive capabilities, thereby helping society to prepare for environmental change and its impacts on humans, ecosystems, and the global climate system. It will be a vehicle for harnessing the resources of the many sub-disciplines of arctic research for the benefit of planners and policymakers.

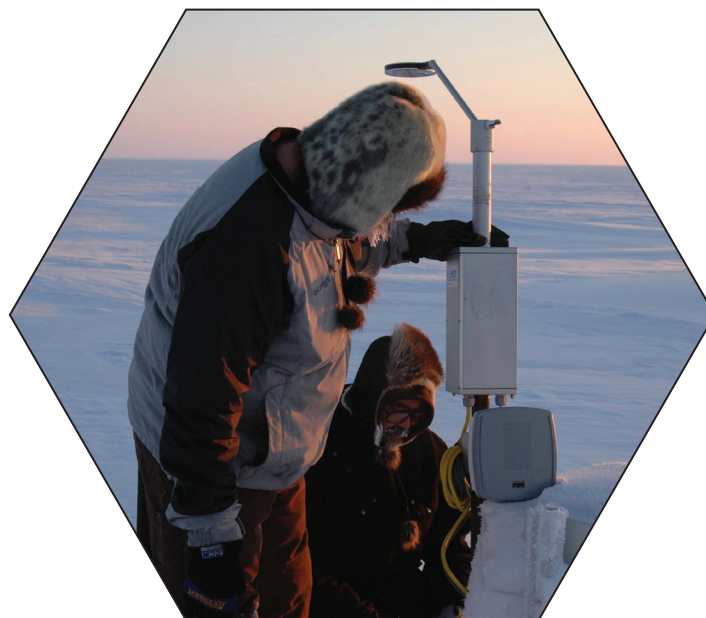
An ASM will build on previous modeling and observations, and it will benefit from ongoing studies of component models that are in varying stages of development. The initial core model will include atmosphere, ocean, sea ice, and selected land components and will be constructed in a manner that allows investigators to add or exchange components as the ASM project progresses. These will include ice sheets, mountain glaciers, dynamic vegetation, biogeochemistry, terrestrial and marine ecosystems, coastal systems, atmospheric chemistry, and human and social dimension modules.

The core focus of the proposed ASM program will be to understand complexity and adaptation in the Arctic System as well as society's role and response in the evolution of that system. The program is designed to complement and work with global Earth System Modeling programs to create reliable probabilistic forecasts

of the state of the Arctic on seasonal to decadal timescales. Therefore, the modeling program must work toward quantifying and reducing uncertainties related to variability of the Arctic System, uncertainty in the models themselves, and uncertainty in society's response and adaptation to arctic change. Basic model development within the ASM program should be focused on improving simulations of the arctic biosphere and anthroposphere.

The ASM program will require coordination of diverse segments of the research community and support for computing infrastructure and software. The coordination function should be guided by a number of working groups and a scientific steering committee. A central facility will fulfill the functions of a project office, data center, and point of international liaison to be shaped and overseen by the steering committee. Dedicated personnel at this facility should provide documentation, testing, and support for the ASM. Proposals for providing these core functions should be sought at the outset of the program.

The program should be approached in stages to make sure it is meeting the overarching goals mentioned above. Stage One will be to fund small pilot projects that allow researchers to demonstrate the capacity of limited-area coupled models to improve understanding of the role of the Arctic in global environmental change. These projects would use high-resolution, Arctic-focused simulations to understand the physics, chemistry, and biology of the Arctic as it undergoes rapid change. If successful, this stage will be expanded to construct a basic regional ASM climate model core. Stage Two incorporates coupled biogeochemical and ecological components into the ASM. Stage Three targets the coupling of those components least ready for integration into the ASM; these include components related to human interaction with the environment. Each stage requires close interaction between ASM model developers and the global modeling and observation communities, and each should be focused on understanding the Arctic as a complex adaptive system.



MOTIVATION

Wide-ranging environmental changes have been documented in the Arctic over the last 50 years. Although many of these changes have been evident since the mid-1970s, it is likely that they began early in the 20th century, prior to the extensive collection of observations in the Arctic region. Regardless of the driving forces, the combined observations and documentation suggest that the Arctic System may be entering a state never before seen in historic times. Complex physical, chemical, biological, and social processes interact to such a degree that it is not possible to understand future trajectories of individual parts of the system without developing holistic perspectives of the complete Arctic system and its connection with environmental change elsewhere on Earth.

All components of the Arctic are interrelated through a network of linkages, feedbacks, and multi-dependent interactions. These connections need to be understood and quantified in order to improve our ability to predict change in the Arctic. A community Arctic System Model (ASM) will strengthen our understanding of the interconnections among system components and related feedback processes. It will be an essential tool used to help construct probabilistic forecasts of the state of the Arctic.

Current efforts to understand the Arctic System and its relationship with global environmental change can approximately be divided into three categories: global climate and pan-Arctic modeling, process studies of components of the Arctic System, and observational monitoring of the current state of the Arctic System. The proposed community regional Arctic System Modeling program

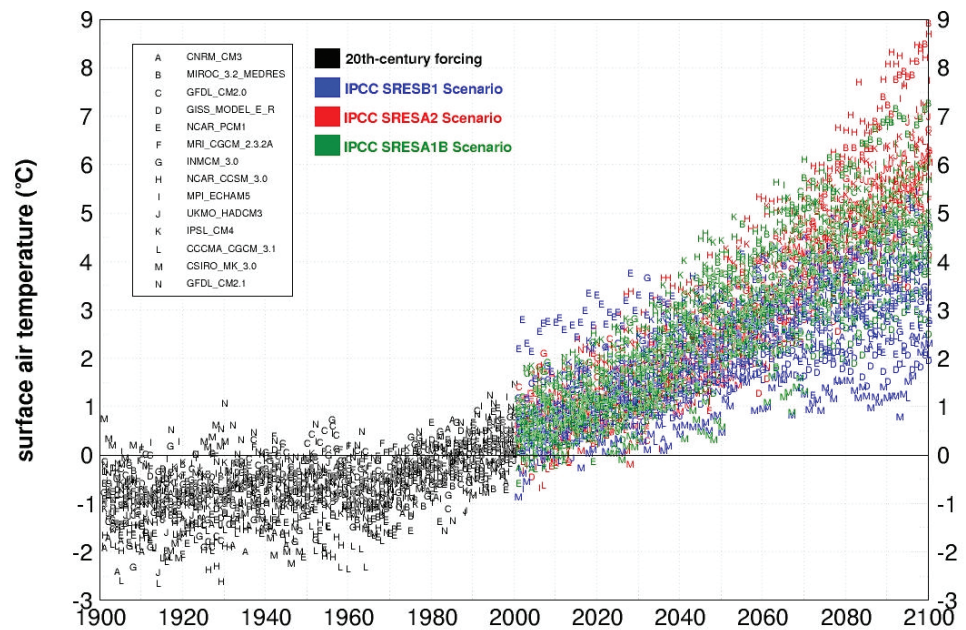


Figure 1: Simulations and projections of two centuries of surface air temperature change, averaged for 60°–90°N, expressed as departures from 1981–2000 means from 14 Global Climate Models. Projections use three Intergovernmental Panel on Climate Change greenhouse gas forcing scenarios: B1 (blue), A1B (green), and A2 (red) (from Chapman and Walsh, 2007).

aims to serve as a bridge between these avenues of understanding. Its goal is to establish clear quantitative insight into the interplay of climate, biogeochemistry, ecology, and human dimensions over a broad spectrum of temporal and spatial scales.

Climate projections for the High North are surrounded by great uncertainty, and existing models cannot capture the combined spatial and temporal patterns of recent arctic changes (e.g., Figure 1). The combined use of global and regional Earth System Models will help identify uncertainties related to the following: a) variability within the Arctic System, b) uncertainty in models' ability to simulate the arctic environment, and c) uncertainty in society's response to environmental change (Hawkins and Sutton, 2009). The combined use of regional high fidelity models and global models is likely to be important in narrowing these uncertainties.

A strong modeling infrastructure and expertise to initiate work on a community Arctic System Model already exist in the United States. However, a clearly defined program is required to focus this infrastructure and expertise toward creating a regional community system model that offers the resolution, complexity, and ensemble sizes sufficient to improve our understanding of how society adapts and contributes to arctic change. These requirements underlie current thinking of how best to develop models for climate impact research (Challinor et al., 2009). The proposed research program would develop a comprehensive understanding of change, attribution of change, and effects of change for the Arctic. It presents a sizeable task that will require strong collaboration within the United States and beyond.

What is the Arctic System?

The Arctic System is the northern dome of the geosphere and biosphere that circulates energy, mass, and nutrients between areas inside the Arctic Circle and the mid-latitudes. The region is subject to climatic extremes; the atmosphere inside the Arctic Circle receives no solar radiation during the boreal winter solstice but the largest solar energy input anywhere on Earth over the summer solstice. On the whole, it has a small annual solar input compared to lower latitudes, causing frequent atmospheric storms and persistent ocean currents to feed energy into the Arctic Circle from further south. In this environment, fresh water is stored and moved in all phases—as a gas, liquid, and polymorphs in snow, glaciers, ice sheets, ground ice, and sea ice (frozen ocean). As an accident of plate tectonics, the Arctic Ocean acts as a freshwater sink for vast areas of North America and Eurasia, indicated in Figure 2. Glaciers discharge into the arctic basin, its marginal seas, and the northern bounds of the Pacific and Atlantic oceans. These marine environments and their terrestrial catchments support a highly productive boom-and-bust ecology that is synchronized with the seasons and sensitive to change in the hydrologic and carbon cycles. Society prospers from the ecosystem through both subsistence and industrial food production; yet the High North remains a formidable environment. It hosts frequent inter-continental flights but offers arduous trans-Arctic passage for seaborne trade (Figure 2). Rapid 21st century sea ice loss is changing this and opening up the Arctic to increased marine shipping (Arctic Council,

2009). It is also attracting interest from resource companies focused on an estimated 30% of the world's gas and 13% of its oil reserves that are probably undiscovered in waters less than 500 meters deep (Gautier et al., 2009).

The southern boundary of the Arctic System is amorphous; it is subject to the moving dynamics of the atmosphere and ocean, which exchange energy, mass, and nutrients with adjacent regions. In order to simulate fluxes across the Arctic Circle, a regional Arctic System Model must necessarily include key features of the Earth's atmosphere, hydrosphere, and biosphere extending south of the High Arctic. The High Arctic is the region within the July 10°C surface air isotherm encircling the North Pole (Treshnikov, 1985; Figure 2). Interactions between the geosphere and biosphere are closely coupled, and so a reasonable southern perimeter on the total system can be described in terms of the boreal atmospheric, oceanic, and cryospheric climate and the extent of the arctic drainage basin. In the atmosphere, the mean Icelandic and Aleutian lows result from frequent northward passage of respective Atlantic and Pacific storms that move energy and moisture into the Arctic. In the ocean, currents pump warm water into the High Arctic from the western boundaries of the Atlantic and Pacific oceans. A southern system perimeter must be set sufficiently far south to include processes that modify this oceanic inflow before it reaches the cryosphere. The southern perimeter of the arctic cryosphere closely matches the surface air 0°C isotherm that

encircles the North Pole. The region enclosed by this contour includes mean sea ice extent, mountain glaciers, and the Greenland Ice Cap. It also includes permafrost and ground ice, which influence the hydrology of land draining into high northern seas, as seen in Figure 2. One can superimpose these features to arrive at the following definition of the Arctic System:

The Arctic System as defined here consists of the geosphere and biosphere north of the boreal mean decadal 10°C sea surface isotherm, the surface air 0°C contour that encircles the North Pole, and the southern limit of terrain that drains into the High Arctic.

This definition is simple and physically based. It captures the relevant terrestrial and marine ecosystems that are integral to the arctic environment, as demonstrated in Figure 2. Fabricating a perimeter for an open-bounded environment is inappropriate for some polar research but is important for establishing the minimum area relevant to regional Arctic System Modeling and measurement. A caveat of this definition is that air and sea temperatures are subject to climatic drift, but referencing isotherms to a particular decade circumvents this problem. It is preferable, perhaps, to use a period prior to the rapid changes in summer sea ice cover that have occurred during the last decade. Using the 1990–1999 decade, as in Figure 2, the defined Arctic System covers about 12% of Earth's surface, 9% of the global ocean surface, and 22% of the global terrestrial area.

What is the Arctic System?

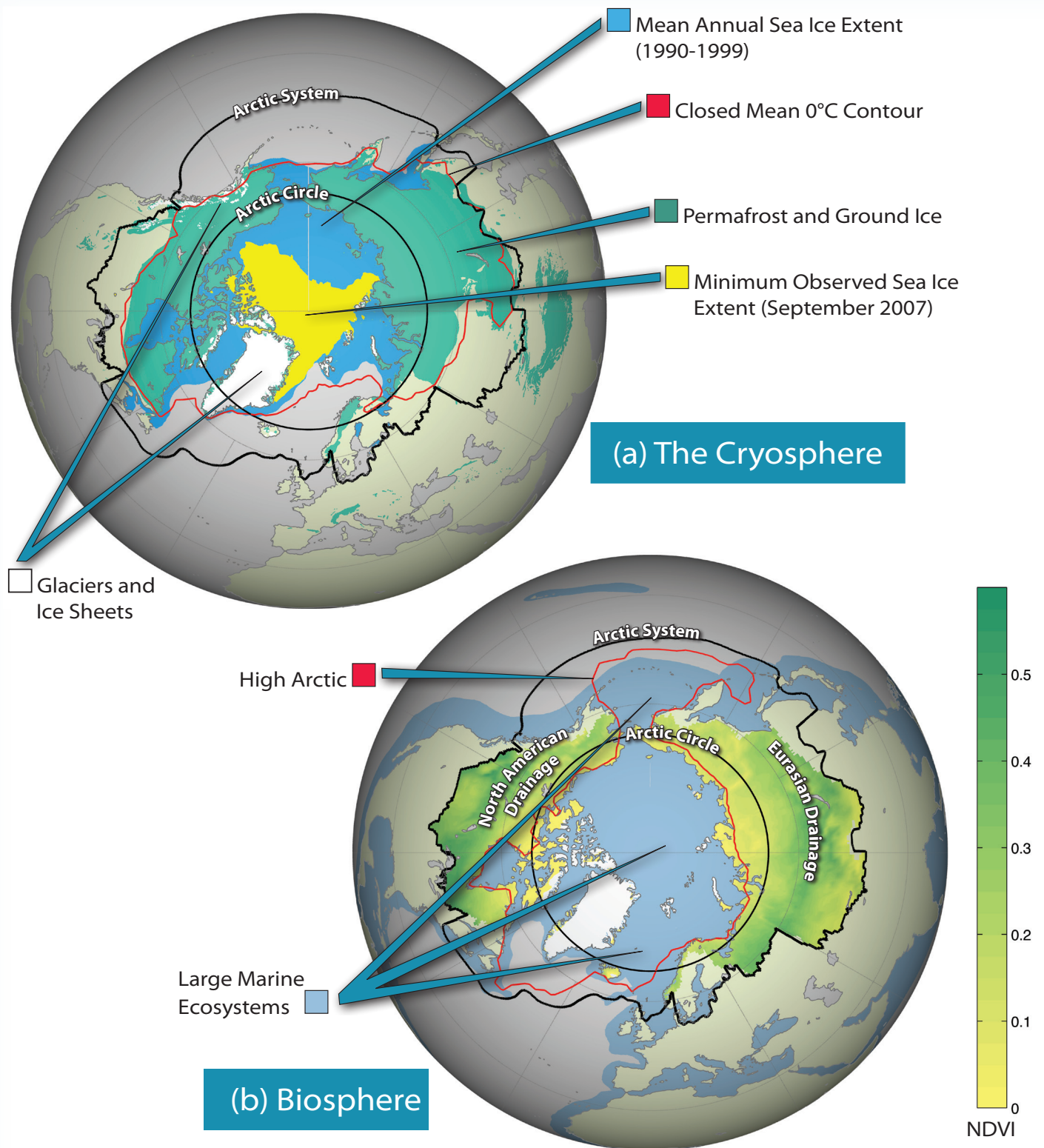
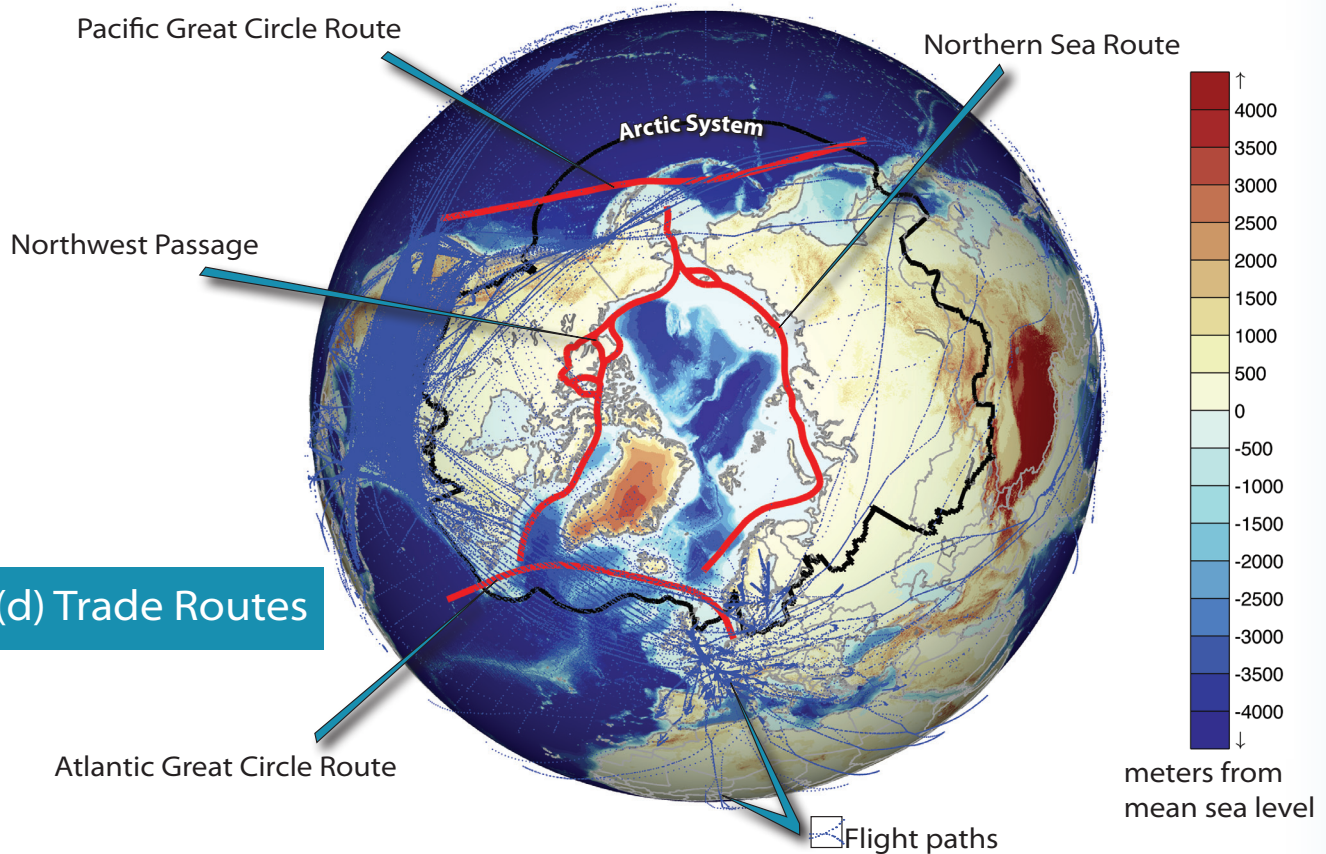
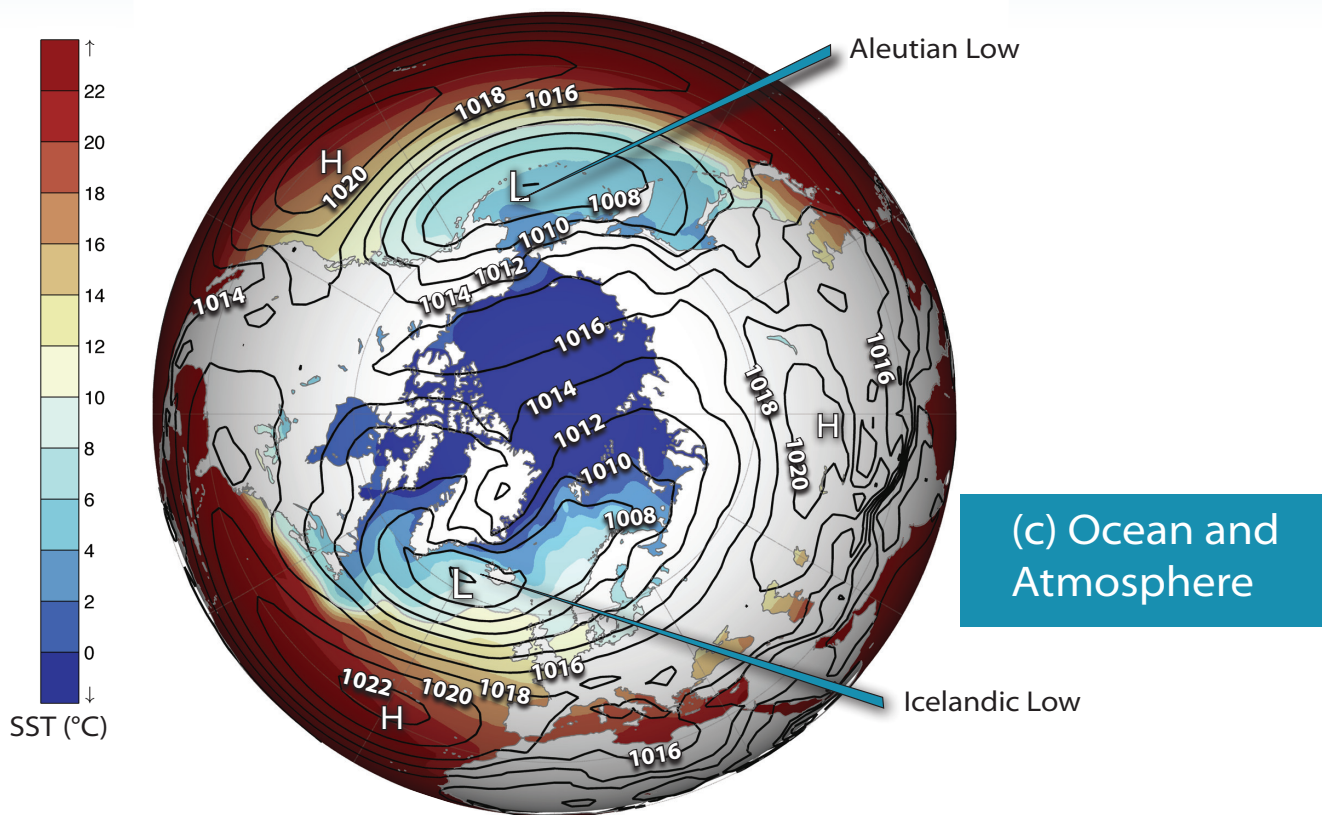


Figure 2: The Arctic System: a) Mean 0°C surface air isotherm encircling the North Pole (red), permafrost and ground ice (from Brown et al., 1998), and mean decadal sea ice extent and 2007 minimum. b) Mean July 10°C surface air temperature contour encircling the North Pole (red), the arctic drainage basin (Serreze et al., 2003) and its mean Normalized Difference Vegetation Index (NDVI) indicating photosynthesis (shaded) and combined Large Marine Ecosystems from the Arctic Marine Shipping Assessment 2009 report. All means are for the decade 1990–1999 unless otherwise indicated. c) Mean sea level pressure (contours) and sea surface temperature (SST; shaded). d) Topo-bathymetry of the Northern Hemisphere (shaded), potential and actual international marine trade routes that transit the Arctic System (red), and in-flight meteorological reports from civil aircraft conforming to World Meteorological Organization reporting requirements for seven randomly selected days in 2006 (blue).



Data sources in order of reference: a) National Center for Environmental Prediction Reanalysis (NCEP2) from Kanamitsu et al. (2002); Brown et al. (1998); Comiso (1999); Cavalieri et al. (2004). b) NCEP2; Richard Lammers (University of New Hampshire); Todd Mitchell (University of Washington); Arctic Council (2009). c) NCEP2; Reynolds et al. (2002). d) Amante and Eakins (2009); Arctic Council (2009); William Chapman (University of Illinois).

The primary goal of the Arctic System Modeling program is to advance investigations of arctic climate variability and change and to understand how these interact with humans, ecosystems, and the global environmental system. The Arctic differs from lower latitudes in fundamental aspects of climate,

biogeochemistry, and ecology. A community Arctic System Model will provide a focal point for developing arctic science and will supply projections conforming to the priorities of climate assessments such as those of the Intergovernmental Panel on Climate Change (IPCC).

The proposed community ASM will be a computer model

that resolves arctic processes with very high resolution and a level of detail that greatly surpasses typical global models. It will be based on a coupled climate model composed of atmosphere, ocean, sea ice, and terrestrial components drawn from existing projects within the arctic research community. Emerging biogeochemical, ecological, human dimension, cryospheric, and terrestrial components will be added during the course of the ASM program, and established ASM components will be continually improved (Figure 3).

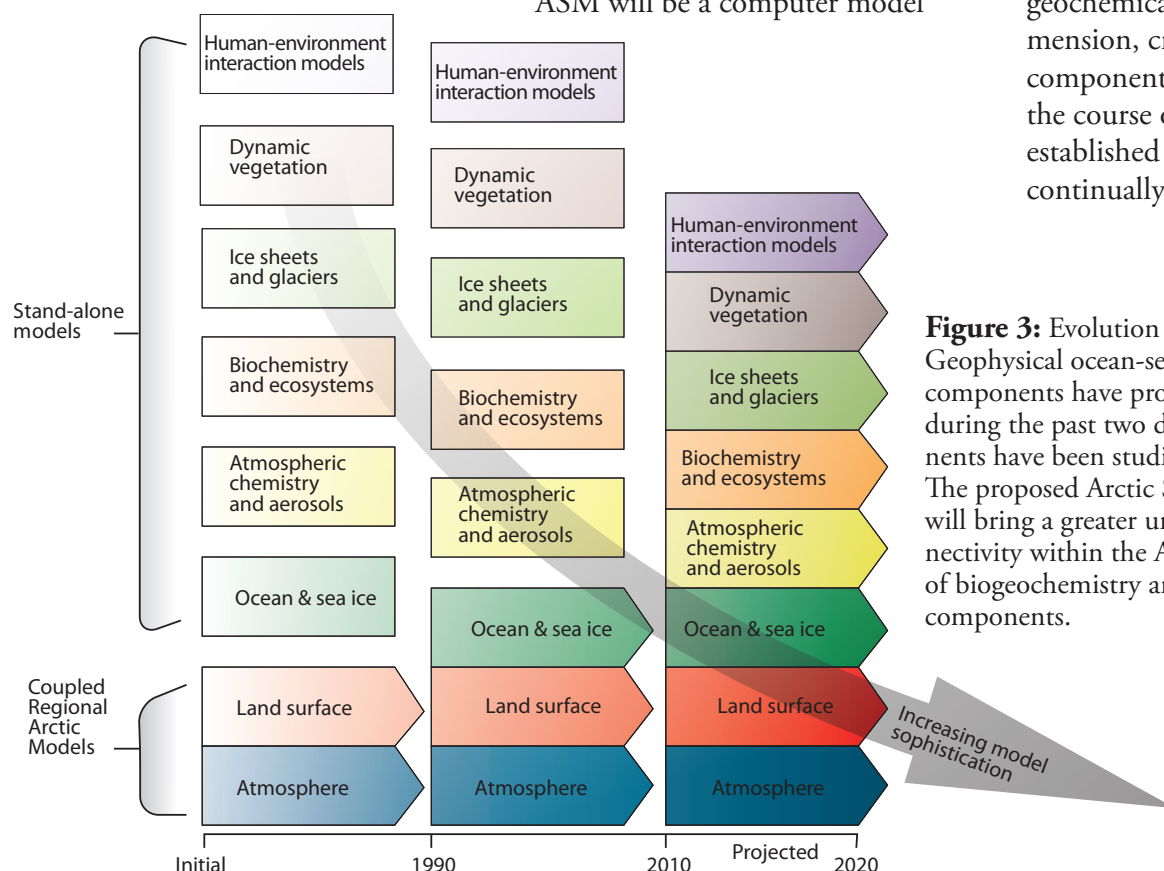


Figure 3: Evolution of regional arctic models. Geophysical ocean-sea ice-atmosphere-terrestrial components have progressively been coupled during the past two decades, while other components have been studied as stand-alone systems. The proposed Arctic System Modeling program will bring a greater understanding of interconnectivity within the Arctic by fostering coupling of biogeochemistry and human dimensions components.

ASM development will strengthen global modeling efforts by creating and improving methods for simulating high-latitude processes. The capacity for interactive nesting inside global earth system models will be built in to the ASM. The model must be able to function as a stand-alone tool for downscaling global environmental information for civil planners, policymakers, and industry and for investigating internal variability in the Arctic System. To achieve these goals, it must remain

at the vanguard of spatial resolution so as to be a preferred test bed for new approaches for simulating the arctic environment.

The proposed ASM program will promote transformative science by treating complex problems through consideration of the interaction of Arctic System components. It will be a widely available and easily usable vehicle for harnessing the collective intellectual resources of the many sub-disciplines of the arctic research community. National and international partnerships will be essential not only to evaluate and use the

model, but also to incorporate new components into the system.

The Arctic System Modeling activity will achieve synergies with the observational community by quantifying the impacts of observing system components, by pointing to process studies needed for developing new and improved parameterizations, and by using observations in model testing and validation. In this respect, the ASM has the potential to integrate various components of Arctic System science with ongoing programs such as the Study of Environmental Arctic Change (SEARCH).

Summary of Capabilities

Coupled regional Arctic System modeling on climate timescales requires a base infrastructure in terms of management, coordination, international cooperation, computation and storage resources, distribution tools, software engineering, and utility programming such as tools for visualization, analysis, and science benchmarking. Existing capabilities include:

- The well-tested and successful Community Climate System Model (CCSM) management structure, which can serve as a prototype for coordination within the ASM project.

- Supercomputing centers that have adequate personnel, hardware, and open data-sharing capabilities for external academic users, such as the Arctic Region Supercomputing Center and TeraGrid facilities, including the Texas Advanced Supercomputing Center and National Center for Supercomputing Applications.
- Software infrastructure for coupling across different model components, which is available for different established coupling frameworks.
- Model development communities maintaining a variety of system component codes.

- Visitor programs, which support international collaboration such as those of the National Center for Atmospheric Research (NCAR), the International Arctic Research Center (IARC), and the Geophysical Fluid Dynamics Laboratory (GFDL).
- International inter-comparison and climate matrix frameworks (e.g., Giorgi et al., 2008).
- Observational networks aimed at model validation and improvement such as the Arctic Observing Network (National Research Council, 2006).

Ongoing Activities

An Arctic System Modeling effort will necessarily build on previous activities within the research community. These encompass modeling and observational studies that have led to a better understanding of the Arctic System. By capitalizing on previous work, an Arctic System Modeling program will accelerate advancement toward addressing pressing science and societal questions related to a rapidly changing environment. Below we outline a partial list of relevant ongoing activities that will benefit a community ASM.

Regional arctic climate modeling studies have traditionally concentrated on atmosphere-land or ocean-ice coupled systems. More recent work has used coupled ocean-ice-atmosphere-land systems. These activities have generally focused on the following:

- Downscaling of climate scenarios for better local interpretation of environmental projections and impact assessments. Examples include the recently completed EU-funded project ENSEMBLES (Ensemble-based predictions

of climate changes and their impacts), which focused on downscaling information for Europe (van der Linden and Mitchell, 2009) and the ongoing North American Regional Climate Change Assessment Program.

- Process studies to improve understanding of arctic climate related processes. This has occurred, for example, through the North American Study of Environmental Arctic Change (SEARCH) and two European projects, Global Implications of Arctic Climate Processes and Feedbacks (GLIMPSE) and Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies (DAMOCLES).
- Comparison between models to identify their strengths and weaknesses. These include the Arctic Ocean Model Inter-Comparison Project (ice-ocean, AOMIP), the Arctic Regional Climate Model Inter-Comparison Project (primarily atmosphere-land, ARCMIP), and the emerging

Coupled Ocean-Ice-Atmosphere-Land Model Inter-Comparison Project (CARCMIP).

- Seasonal prediction experiments, which are an area of increasing research. One such example is the study by Zhang et al. (2008), which used a regional coupled ice-ocean model system for sea ice forecasts.

A number of regional coupled models are participating in these efforts, and improvements to these models are being engineered based on project outcomes. The recently completed joint US-EU project SEARCH for DAMOCLES (S4D) aimed to coordinate arctic modeling and observational activities, and a series of workshops addressed considerable uncertainties in arctic climate simulations (Proshutinsky et al., 2008).

A community ASM will benefit from these programs and from ongoing developments of a variety of modules for the atmosphere, ocean, sea ice, land, biogeochemistry, atmospheric chemistry, ecosystems, glaciers, ice sheets, and the human

dimension. These developments include emerging capabilities for nesting regional models within global model domains and improved ability to gauge model errors and uncertainties. Close collaboration is necessary through inter-comparison projects and an engaged observational community. A number of observational projects are tailored to serve model improvement. Examples of these projects are the Arctic Summer Cloud Ocean Study (ASCOS), SEARCH, and DAMOCLES. A sustained Arctic Observing Network (AON) will improve process-level understanding and allow for better-validated models.

In reanalysis projects, the connection between modeling and observations is clear and necessary. These connections provide gridded datasets physically consistent with available observations and are useful for model validation and improvement. Better models in turn improve the reanalysis and allow for detection and attribution of arctic change. Current and recent arctic reanalysis projects include:

- The Arctic System Reanalysis project (Bromwich et al., 2010).
- Ice-ocean analysis projects as part of the Global Ocean Data Assimilation Experiment (GODAE; Dombrowsky et al., 2009).

These activities are only a selected subset of current arctic science programs that provide a foundation for an ASM. In turn, a community ASM effort will provide a research focus and ultimately a tool that can synthesize the knowledge gained from these often disparate arctic research activities. It will promote accelerated understanding of arctic change and its consequences for humans, ecosystems, and the global system.

A Complex Adaptive System

The arctic biological, climatological, hydrological, and thermal regimes are fully coupled and cannot be completely understood individually (Figure 4). For example, plant cover is integral to soil moisture and permafrost dynamics. The ecosystem, in turn, provides feedback to both the local climate and hydrology through water vapor, carbon dioxide (CO_2), and methane (CH_4) fluxes to the atmosphere. Atmospheric circulation patterns change seasonally and have complex interactions with ocean circulation, sea ice, and land-surface energy and water fluxes. Among these interactions, the link between the atmosphere and snow cover extent is relatively well established. Snow cover influences the surface energy budget not only by its dominating impact on albedo, but also by insulating the surface in winter and by recharging rivers and ponds in spring. The Arctic Oscillation (AO) correlates with surface air temperatures, which in turn affect snow cover. The observed recent decrease in Northern Hemisphere spring/summer snow cover thus likely reflects large-scale atmospheric events.

Continued losses of sea ice, especially in coastal and marginal seas, affect regional climate and marine and terrestrial ecosystems. The timing of river runoff will be impacted by earlier spring melt events and by degradation of permafrost, likely influencing sea ice formation. These land-atmosphere-ocean feedbacks extend far beyond coastal

regions and influence the Arctic Ocean as well as other oceans of the world. Recent analyses of periodic atmospheric phenomena such as the AO suggest interconnections among the major land, ocean, and atmospheric components of the larger Arctic System. Salinity anomalies originating with freshwater pulses from the Arctic have had oceanographic, climatic, and economic consequences beyond the Arctic Ocean, extending to the North Atlantic. Process studies and modeling analyses help us to understand interconnections within the system and how the Arctic may continue to respond to a changing climate.

No single piece of the system is independent, and to fully understand even a part of the system, we need to coordinate and integrate synthesis studies of the processes, linkages, and causes of variability in the water and energy cycles (Figure 4). Because the Arctic is a vast and sparsely populated area, where integrated system studies are relatively new, there is much we do not know. Developing a sound predictive capability of climatic change and system-level responses is challenging, especially in light of the limited pool of observations of the region's severe climate. However, the very same factors that create difficulties also increase the value of that understanding. The Arctic is one of the few systems on Earth in which direct human influences are minimal. The complexity and sensitivity of the arctic terrestrial and

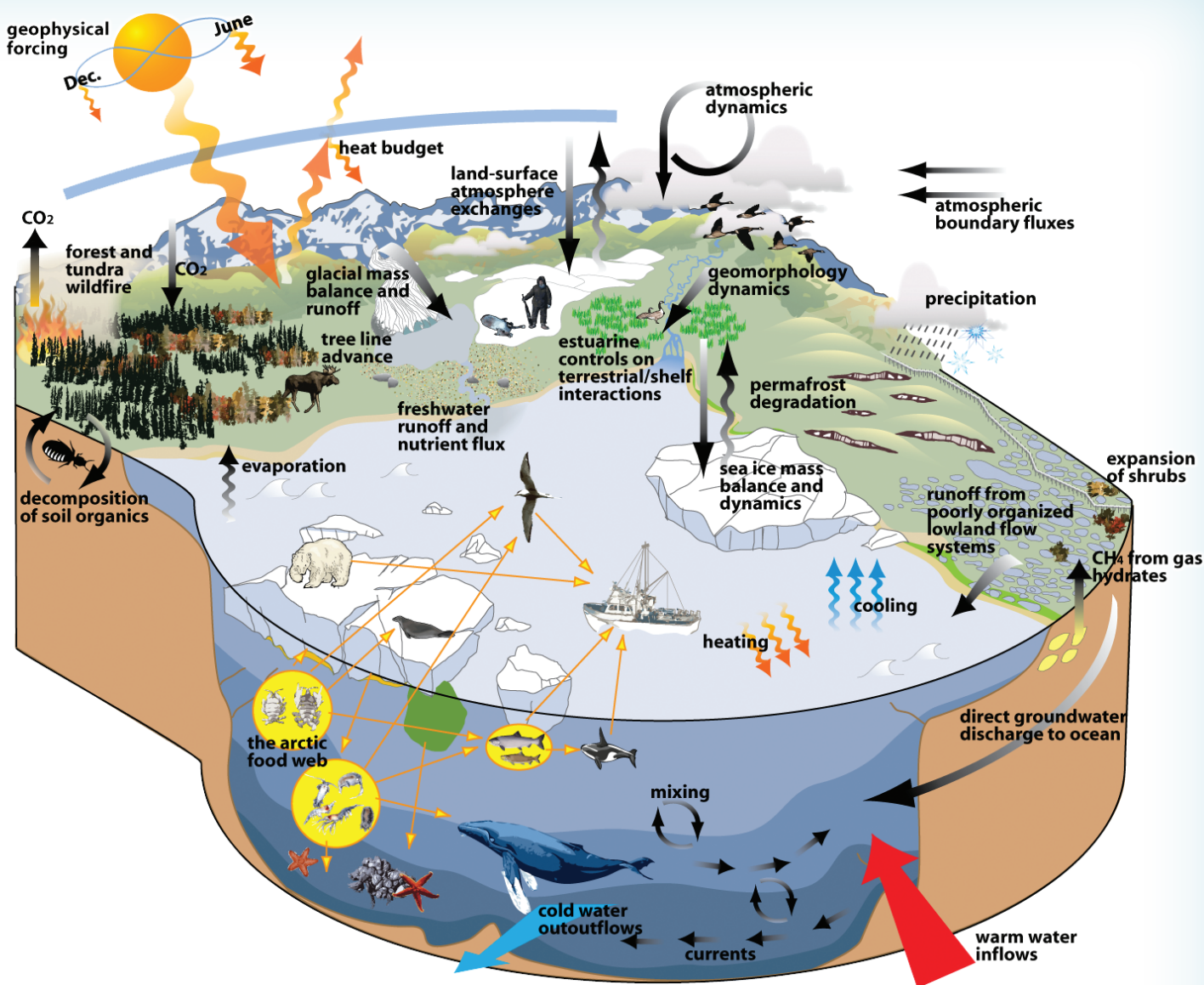


Figure 4: The Arctic is a highly coupled system with clear linkages and strong inter-dependence among system components.

marine system responses to change yield broad, yet consistent, evidence of rapidly changing physical, biological, and social systems. Emphasis upon collaboration across disciplines with integration and synthesis across national and international arctic research communities presents a viable approach to understanding the complicated linkages within the

arctic biological, physical, and social systems.

The arctic is a highly coupled system in which the individual components are strongly interdependent. Theoretically, a change in one variable in a part of the Arctic System might initiate a cascade of effects throughout the system. These connections need to

be understood and quantified in order to achieve a level of predictability. It is a complex adaptive subsystem of the Earth undergoing rapid change. Therefore, it offers a striking opportunity to serve as the basis for new environmental management tools that may subsequently be adapted and applied to other regions of the globe.

International Collaboration

Development of an ASM will benefit greatly from an international exchange of knowledge, tools, data, and component models. Individual countries with strong arctic interests are pursuing their own regional arctic modeling programs, and the existence of multiple limited area models of the same region is important for improving estimates of model uncertainties (Giorgi, 2005; Hagedorn et al., 2005). An ASM infrastructure that is open to the international community would allow different research groups to adopt some components of an ASM into their own models, and change them as they see fit. This would help generate a cluster of regional arctic models with a sufficiently diverse lineage to further the understanding of model uncertainties. Ease of sharing numerical tools between different nations' models could be enhanced by the use of Modeling Environments (e.g., HOME, 2005).

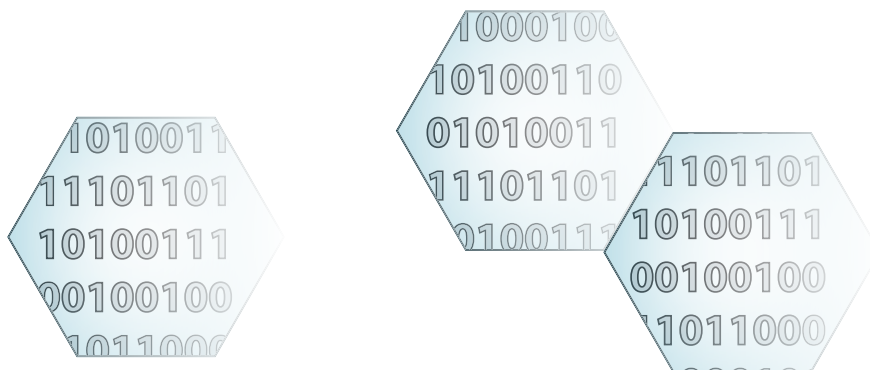
Discussions at the third ASM workshop (Montreal, 2009) focused on the best way to organize a loose but growing network of international modeling groups working on regional Earth System Models of the Arctic. Workshop participants agreed that a grassroots committee should be formed to coordinate future international ASM meetings. They recommended that a modest facility be established at an international

research institute to assist international collaboration. This facility would provide centralized sharing of model output, boundary and initial conditions, and specialized observational datasets for model evaluation (Roberts et al., 2010). Rather than housing and chronicling data, the facility would provide a portal for research groups to share data and code. This idea builds on the success of existing portals that amalgamate global climate information for the research community (e.g., Diamond and Lief, 2009). The proposed effort must not replicate the work of data centers, but instead provide practical help to accelerate and assist international collaboration including:

- Compilation of datasets from *in situ* measurements for evaluating and comparing models.
- Development of statistical tools so that models may be used to help identify biases and gaps in observational networks.
- Preparation of boundary and initial conditions from global models for coordinated multi-model experiments.
- Maintaining an up-to-date inventory of projects and experiments available for evaluation and intercomparison.

An Arctic System Modeling program should contribute to international programs, such as the IPCC. This will help in providing probabilistic arctic projections that enable uncertainty to be apportioned between model projections, the arctic system itself, and human actions and responses in that system.

The human dimensions components of regional models are particularly underdeveloped, and the proposed Arctic System Modeling program would benefit from supporting an international working group to improve human dimensions modeling for the Arctic. Pan-Arctic nations share certain climatic, economic, historical, and cultural commonalities. It makes sense to establish an international working group aimed at creating human dimensions components that take advantage of these commonalities, but can also be applied to individual Arctic states. The proposed International Arctic Human Dimensions Working Group would facilitate comparison of human dimensions modules in regional arctic models and contribute to the evolving science of understanding human interactions with the environment (e.g., Moss et al., 2010).



Recommended Approach and Strategy

The proposed ASM should be developed in a framework that allows for dynamic coupling between all models. A core model initially will include those components that are the most mature and ready for use—atmosphere, ocean, sea ice, and land surface components. A project office will provide support for a single version of the ASM. However, the model should be constructed in a manner that allows individual investigators to replace any model com-

ponent with a different model or add new model components if desired. This strategy reflects the need for a focused effort to develop the core model that is sufficiently flexible to lead to completion of an all-encompassing ASM. This approach is similar to that used for the NCAR model CCSM and its evolving Earth System Model counterpart. Using this approach, a “standard” open-source release of the model would be

supported by a central facility, but the broader scientific community would be encouraged to modify model components or develop new ones as appropriate for their specific research interests (see, e.g., Voinov et al., 2010). New model components would be added to the central, open-source version from an evolving pool of community developments after acceptance and recommendation from ASM working groups.

Model Constituents

The core components for the ASM should be models that have already been applied and validated for use in the Arctic and have a known skill in simulating the Arctic. This will start the ASM from a well-documented base and allow for rapid progress in exploring coupled processes in the system model. The core model components should be publicly available and have adequate documentation and support infrastructure in place. An example of such a model is the Weather Research and Forecasting (WRF) atmospheric model, which was developed collaboratively by several U.S. institutions, including NCAR and the National Oceanographic and Atmospheric Administration (NOAA). It has an active user community that is continually making improvements to the model, an extensive documentation, and a strong user support structure in place.

It is strongly advised that components contributing to the physical core of the ASM be adapted from existing software used and maintained at established modeling centers such as GFDL, NCAR, and

Los Alamos National Laboratory (LANL). The ASM program must concentrate on coupling the core model components and adapting them to the Arctic where necessary. No basic development work should be attempted on the physical core unless it is absolutely necessary for bringing the accuracy of ASM simulations to within a defined tolerance. If so, this work should be conducted in close consultation with the modeling center from which the concerned model derives. The prime ASM focus should be on expanding capabilities of its biospheric and human dimensions components.

An ASM will encompass many more than the four staple climate model components—atmosphere, ocean, sea ice, and land surface. Over time, ice sheets, mountain glaciers, dynamic vegetation, biogeochemistry, terrestrial and marine ecosystems, coastal systems, atmospheric chemistry, and human and social dimensions will be added. Some of these models are nearly as well developed as the core model components and could be implemented in the ASM in the near future. Others

require significant development before being suitable for interactive coupling to a system model. As these model components are developed, it will likely be advantageous to implement them in a one-way coupled, or off-line, mode so that the behavior of the model can be evaluated prior to fully interactive coupling within the ASM. We expect that the development of additional component models will be funded through open funding calls that will coordinate model development efforts and provide a pathway for their inclusion in the full ASM.

It is recommended that a well-documented, publicly available coupling framework be used to assemble the ASM. Couplers are fast-evolving pieces of software, and it is suggested that the technical specifications of the coupler be standardized and facilitate ongoing development of software infrastructure used by the model. The coupler must obey fundamental mass and energy conservation laws. It must be able to run on a wide variety of platforms, be computationally cheap, and support different component-model

mesh types. The ASM program coupling software must be chosen early because it will form the nexus of the ASM community. Proposals from groups interested in providing and supporting a coupler should

be sought at the outset of the ASM program.

In order for the ASM to achieve its potential, the model must be readily available to the research community and widely used. This will require that the model code is

easily accessible, that all aspects of the model are well documented, and that a support infrastructure exists. User tutorials and workshops would allow new users to become familiar with the modeling system and share results.

Model Domain

The ASM should not be tied to a specific domain, but should instead offer flexibility to change the arctic regions it simulates and the resolution it uses to do it. It must have the ability to be nested interactively (two-way nesting) inside a global model, and it must be able to run as a pan-Arctic model with non-interactive boundary conditions provided from global model output (one-way nesting).

This capability may be achieved in two ways. One approach is to develop an ASM as a one-way nested regional coupled model with its own unique mesh and core code, and

then establish a two-way nesting capability with a global model once the stand-alone ASM is established. Another option is to start ASM work in concert with an existing global modeling project that uses computational meshes that may easily be adapted to offer exceptional and consistent resolution over the Arctic. In this case, the ASM would be a highly specialized entity of a global model and would share code and the arctic grid with it. This second option would require specific numeric properties of a parent global model in order to allow the ASM portion of the global domain to run

as a one-way nested regional model in addition to being used in global simulations. In this sense, the model would be an embedded ASM inside a global model (see Figure 5).

An embedded ASM could negate boundary condition problems that can arise from nesting limited area models inside larger simulated domains. It could ensure that the ASM always remains ahead of ever-improving global model resolutions and would expedite a seamless transfer of computer code and techniques to a global model from an ASM. On the other hand, an ASM developed as a separate entity has the advantage

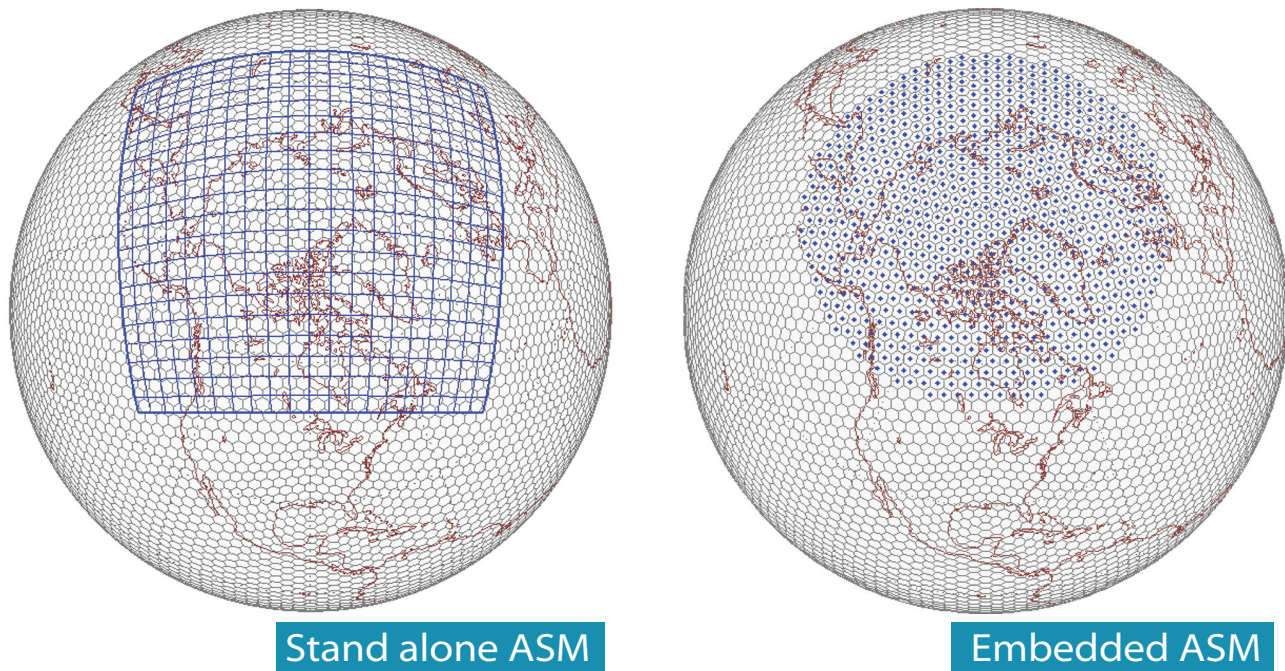


Figure 5: Schematic of two visions of an Arctic System Model: stand-alone and embedded models (arbitrary blue domains). The stand-alone ASM is configured separately from a global model (gray mesh) in which it is nested, while the embedded ASM shares code and a region of the component model computational meshes with the global model. The embedded ASM domain can be used as a regional (one-way nested) model in addition to being a local element of global simulations (two-way nesting). The global model component in this example uses a geodesic grid that can be adapted to focus resolution on the Arctic.

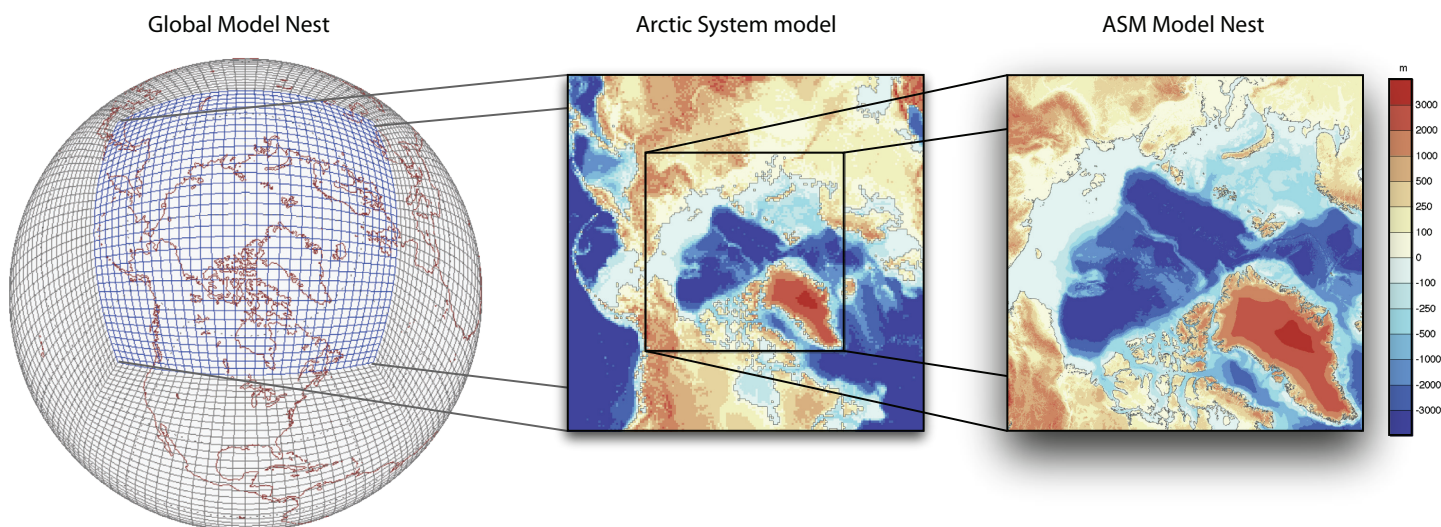


Figure 6: Schematic of proposed ASM nesting capabilities. An arbitrary ASM domain (center) is nested or embedded in a global model (left) in addition to being nested inside itself (right) to focus resolution on arctic regions of specific interest. In this example, the global model has an adaptive cubic mesh focused on the Arctic. Color shading provides an example of the improvement in topo-bathymetry representation between a 50km mesh (center) and a 5km resolution nest (right) as might be achieved through multiple nestings.

of using a computational mesh that is not subject to variable arctic resolutions of some global area-focused grids. A non-embedded, or stand-alone, ASM will also maintain complete research focus on arctic processes without the temptation to stray to broader issues of a parent Earth System Model. Many innovative computational grids and nesting techniques that are currently in use could benefit both of these visions of an ASM, and they should be carefully evaluated. The central theme of both visions is that the resultant model would be strongly “Arctic-centric,” and both approaches are likely to be equally useful to the overall goals of the program.

It is important to emphasize that both regional and global models of the Arctic are essential for understanding the relative contributions of model error, human response scenarios, and system uncertainties in environmental projections. Output from global and one-way nested regional models can be combined to

create probabilistic environmental forecasts (Giorgi, 2005). The emphasis of the ASM program must be toward creating a unified model of the Arctic, whereby resolution and processes thought to be important for weather forecasts are merged with those of climate models (e.g., Hurrell et al., 2009). By virtue of the limited domain size, a one-way nested Arctic System Model will be able to provide high resolution, a large number of resolved processes, and many-member ensembles that will be prohibitive in a global model of similar resolution. Therefore, two-way nesting should not be the initial focus of an ASM program. Instead, the aim should be on providing information that global models cannot provide, thus enhancing the overall capabilities of the arctic research community. Precise grid configuration should be only one of many factors considered when assessing the worthiness of component models for inclusion in an ASM.

Regardless of the computational mesh used, an ASM must have the flexibility to provide boundary conditions and resolution for down-scaling to particular arctic processes and problems. For example, efficient simulations focusing on the ablation zone of the Greenland ice sheet require a horizontal resolution on the order of 1km, but elsewhere in the Arctic these simulations need only moderate resolution (~50km). One way to focus the ASM domain on individual problems is by nesting high-resolution versions of the ASM within lower-resolution versions of itself (Figure 6). Given the current state of well-documented publicly available models that are likely to be candidates for an ASM core, this is the initially preferred method for providing focused resolution. However, techniques for focusing resolution using adaptive grids in Earth System Models are rapidly evolving, and alternate methods should be considered for later versions of an ASM.

Organization and Coordination

There will be a need for careful coordination of the evolving model because an ASM will require involvement of diverse segments of the arctic research community. A host of support functions, including software support, model diagnostics, and computing infrastructure, will be needed as well. In this section, we address the organization, coordination, and support functions. Computing infrastructure is addressed in the following section.

Our recommendation for oversight draws mainly upon experience from the CCSM. This is perhaps the most successful of the recent modeling activities to incorporate strong participation from the broader research community. A hallmark of the CCSM has been an effective Scientific Steering Committee (SSC), which provides scientific leadership including oversight of working groups, coordination of model experiments, and decision-making on model definition and development. The SSC consists of several representatives of funding agencies, NCAR scientists who are heavily involved in the CCSM program, and scientists from the user community. In addition, the co-chairs of the working groups participate in the meetings of the SSC. CCSM contributors point to two reasons for the effectiveness of this committee: first, the SSC is empowered, and, second, its leadership (i.e., chair) has been strong. Lessons learned from the CCSM's success are that a Scientific Steering Committee is desirable and that its composition and roles must be given careful consideration. We recommend a similar committee for the ASM. An ASM steering committee would control the timing

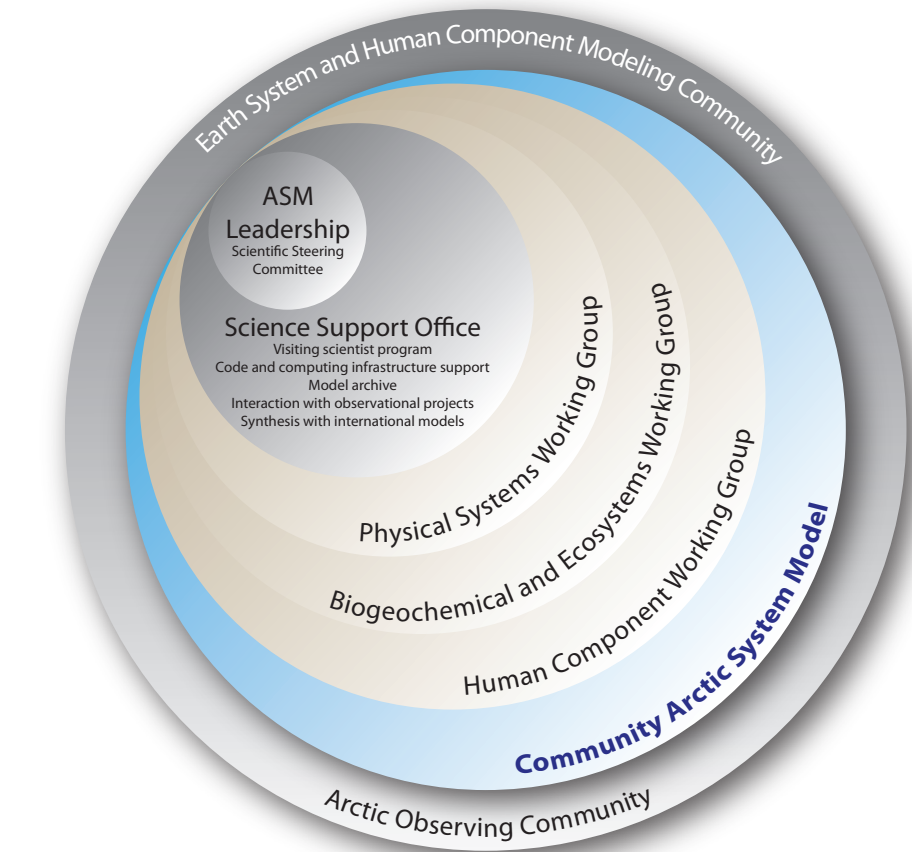


Figure 7: Organization of the Regional Arctic System Modeling program.

and content of official releases of new model versions and would help guide funding agencies on the future requirements of PI-driven research that would aid model development.

The second vehicle for effective coordination of the CCSM has been a set of working groups. CCSM working groups are relatively small teams of scientists who work on individual component models, specific coupling strategies, or scientific foci. Membership in each working group is open, and each is co-chaired by one NCAR scientist and one non-NCAR scientist. Each working group takes responsibility for developing and continually improving its CCSM component, consistent with wider CCSM goals and design criteria. Each working group decides

its own development priorities and work schedules, subject to oversight by the Scientific Steering Committee. The number and foci of CCSM working groups have evolved over time, but currently there are working groups for the atmosphere, land, land ice, ocean, high latitudes (sea ice), biogeochemistry, chemistry-climate, climate variability, climate change, paleoclimate, and software engineering. We foresee a similar structure for the ASM, although its smaller size relative to CCSM should limit the number of working groups. Nevertheless, in anticipation of the new components to be added to ASM as it evolves, it behooves the ASM to form working groups to begin planning well before those components are implemented.

It is recommended that three ASM working groups be established: one for physical systems relating to the geosphere, one for biogeochemistry and ecology (biosphere), and one especially devoted to simulating human components (Figure 7). This emphasizes the key driver of the ASM program, which is to understand the complexity and adaptation of the Arctic System and society's role and response in the evolution of that system. The ASM human dimensions working group should be interconnected with, or strongly contribute to, an International Arctic Human Dimensions Working Group mentioned in the "International Collaboration" section of this report. The working groups would take responsibility for technical details of official ASM releases and provide feedback to the scientific steering committee on future requirements to improve the model.

Support functions will be crucial to the success of the ASM if the activity is indeed to be more than a loose federation of coupled modules. Crucial support functions will span the organizational duties of a project office, including software and linkages to the observational data required for validation, assimilation, and boundary conditions. We see the need for a core facility that could coordinate these functions. Require-

ments of the establishment of such a facility are as follows:

- Its location must be determined through an open competition in response to a call for proposals.
- The functions of a project office—software support, data access, and computational resources—must be consolidated to the extent feasible.

The attributes and services to be provided by the ASM project office will be determined and guided by the Scientific Steering Committee, yet we expect that the responsibilities will include the following:

- a. An active visitor program with resources to support short- and long-duration stays by national and international participants in the ASM activity.
- b. Coordination of community involvement through workshops, dissemination of project information, promotion of the ASM activity, and preparation of project reports. These functions should be consistent with guidance from the Scientific Steering Committee.
- c. Dedicated support staff to be responsible for ensuring ease of access to, and use of, the ASM.
- d. Integration of observational and modeling activities within the ASM framework. Access to observational datasets, field program measurements, and other compilations of data will enhance this function. This function can

extend to dataset compilation and formatting required for data assimilation and observing system experiments.

- e. Provision of scientific support through a resident core of scientists with expertise in model development, model applications, and arctic observational studies.
- f. Facilitation of model parameterization test bed activities.
- g. Provision of commonly used fields such as those required for lateral boundary forcing and for model validation.
- h. Scientific benchmarking through the evaluation of model simulations, diagnosis of model errors, and facilitation of model inter-comparisons.
- i. Synthesis activities with international modeling groups as described previously in this report, and in Roberts et al. (2010).

A central facility that performs all the above functions would likely be the most efficient way to meet the needs of the ASM. However, it is possible that the needed support functions could be achieved through a distributed approach in which some of the functions are provided elsewhere.

The exact shape and responsibilities of this facility should be determined by the Scientific Steering Committee in consultation with program managers at the supporting funding agencies. A summary of the proposed organizational framework is provided in Figure 7.

Infrastructure Needs

An Arctic System Modeling activity will require extensive infrastructure support, including dedicated up-to-date computing resources. If the ASM is to provide a state-of-the-art model for use and development by the broader scientific community, standard software engineering practices with revision control must

be used in the coding, coupling, and testing of different component systems. The model must be well documented, and user services should allow easy visualization and analysis of simulation data. The success of this project will depend on the formulation and maintenance of a modeling system that is easily

accessible, extensible, and usable. We recommend that, in addition to dedicated computing resources, dedicated software engineering personnel will oversee the documentation, testing, and general software engineering support for the ASM activity.

Core Activities and Phased Implementation

All development associated with the Arctic System Modeling program should be aimed toward at least one of five core activities:

1. Decadal arctic climate projections.
2. Weekly and seasonal arctic prediction.
3. Downscaling (upscaling) from (to) global climate models for *in situ* arctic observations and civil operations.
4. Model-and-observation synthesis aiding an arctic observing system design, interpretation of measurements, process studies, and model validation.
5. Understanding complexity and adaptation of the arctic system and society's role and response in the evolution of that system.

The overarching aim of ASM development, to reduce uncertainty in seasonal to decadal arctic projections, should be addressed, in part, by including multiple ensemble members in ASM results. Model-and-observation synthesis may require application of data assimilation techniques, which may best be implemented in collaboration with ongoing reanalysis projects. Each of these five core activities would lead to an improved understanding of arctic variability and change.

The ASM program should progress in stages, starting with proof-of-concept projects to establish a strong case for arctic system modeling, and culminating in the inclusion of coupled human dimension modules as a mature ASM, as illustrated in Figure 8. Stage One of the Arctic System Modeling program should be initiated by funding a group of short-lived pilot projects awarded through competitive grant applications.

Pilot projects will provide an opportunity for researchers to present a case for the unique capacity of Arctic-centric coupled system models to improve understanding of aspects of the Arctic and its role in the global environment. The projects should allow researchers to use models familiar to them to facilitate swift progress in their work. Rapid success from these proof-of-concept projects should result in increased buy-in from the broader research community for a fledgling ASM program. Eight potential proof-of-concept topics, similar to the following, could gain quick advantage from ongoing model developments using high-resolution (<10km) coupled Arctic System simulations and probabilistic modeling techniques.

1. **Attribution of arctic amplification:** Contributions of arctic processes, including cryospheric changes, to enhanced warming signals relative to the global average, segueing with Topics 2 and 4 (below).
2. **The trajectory of arctic sea ice cover:** A high fidelity, coupled reconstruction of changes in arctic sea ice volume during the satellite era to advance our understanding of rapid 21st century ice loss to provide the best indication yet of potential future changes and the rate of change in arctic sea ice cover. This could use several emerging coupled regional system models, establishing the accuracy of base-model simulations for use in other pilot projects, such as those involving biogeochemical processes that affect the surface radiation budget (Topic 6, below).
3. **Changes in the surface carbon fluxes:** A high-resolution study of CO₂ and CH₄ exchanges with the atmosphere from terrestrial and

maritime sources using current biogeochemical and ecosystem codes in conjunction with a high-resolution coupled regional arctic system model. This study would spearhead our understanding of the potential of parts of the arctic system to transform from net sinks to sources of greenhouse gases, providing insight into possible mitigation strategies, complementary to Topic 8 (below).

4. **Processes affecting Greenland melt:** A process study using a coupled atmospheric model to demonstrate how arctic atmospheric circulation and surface conditions may alter rates and zones of ablation over the Greenland ice sheet, and demonstrating how results differ from low-resolution global modeling simulations. This topic will help address questions about possible causes of arctic amplification in Topic 1 (above).
5. **Coastal vulnerability:** A survey of the potential for an arctic-centric coupled system model, used in conjunction with a coastal systems module, to provide unprecedented guidance for planners and engineers of the potential for coastal transmutations caused by reduced arctic sea ice cover and altered storm activity.
6. **Biospheric feedbacks to atmospheric composition:** An analysis of how the rapidly changing arctic summer ice edge (Topic 2, above) and associated biological activity could alter cloud composition and climatology. This requires use of a marine ecosystem and biogeochemistry module in conjunction with a high-resolution, coupled system model incorporating atmospheric chemistry and aerosol calculations.

7. Short-term effects of permafrost degradation:

High-fidelity, coupled simulations indicating both the response of permafrost to climate change and, in contrast to most existing studies, the ability of permafrost reduction to alter arctic climate. This would require use of a high-resolution system model with an active permafrost layer and a terrestrial ecosystem model and is complementary to Topic 3 (above).

8. Agent-based decisions:

A proof-of-concept human dimension study whereby an agent-based model is used to understand how certain human responses to the simulated environment provide feedback to geospheric and biospheric components discussed in Topics 1-7 (above).

Each of these topics focuses on understanding aspects of the physics, chemistry, and biology of the Arctic

as it undergoes rapid change. Science related to each is explained in the proceeding Arctic System Model Vignettes section. Several topics would make use of emerging model components that are yet to be used universally in arctic simulations. Moreover, each potential pilot project requires model-and-observation synthesis, a central theme of ASM development. However these mini-projects are chosen, it is strongly recommended that they be tightly focused and quickly achievable by the applicants.

With strong cases established in Stage One for the continuation of the Arctic System Modeling program, subsequent work in this initial stage will focus on constructing the regional ASM climate model core. As previously mentioned, a single set of atmospheric, ocean, sea ice, and terrestrial model components needs to be chosen for the

community model, and each component must already be in a high state of readiness for the purpose of Arctic System Modeling. Selection of the core components should take place through competitive grant applications to capitalize on existing efforts. A simultaneous call for proposals to provide and support coupling software for the ASM program must be made. It is important to note that by the time this report is acted upon, several working arctic coupled regional climate models will likely be up and running. This means that the timeframe to obtain the regional climate core of the ASM could be relatively short. Moreover, it is likely that some models used in Stage One pilot projects will be selected for use in the ASM core, thus providing a quick work transition from some pilot projects to central regional climate modeling activities.

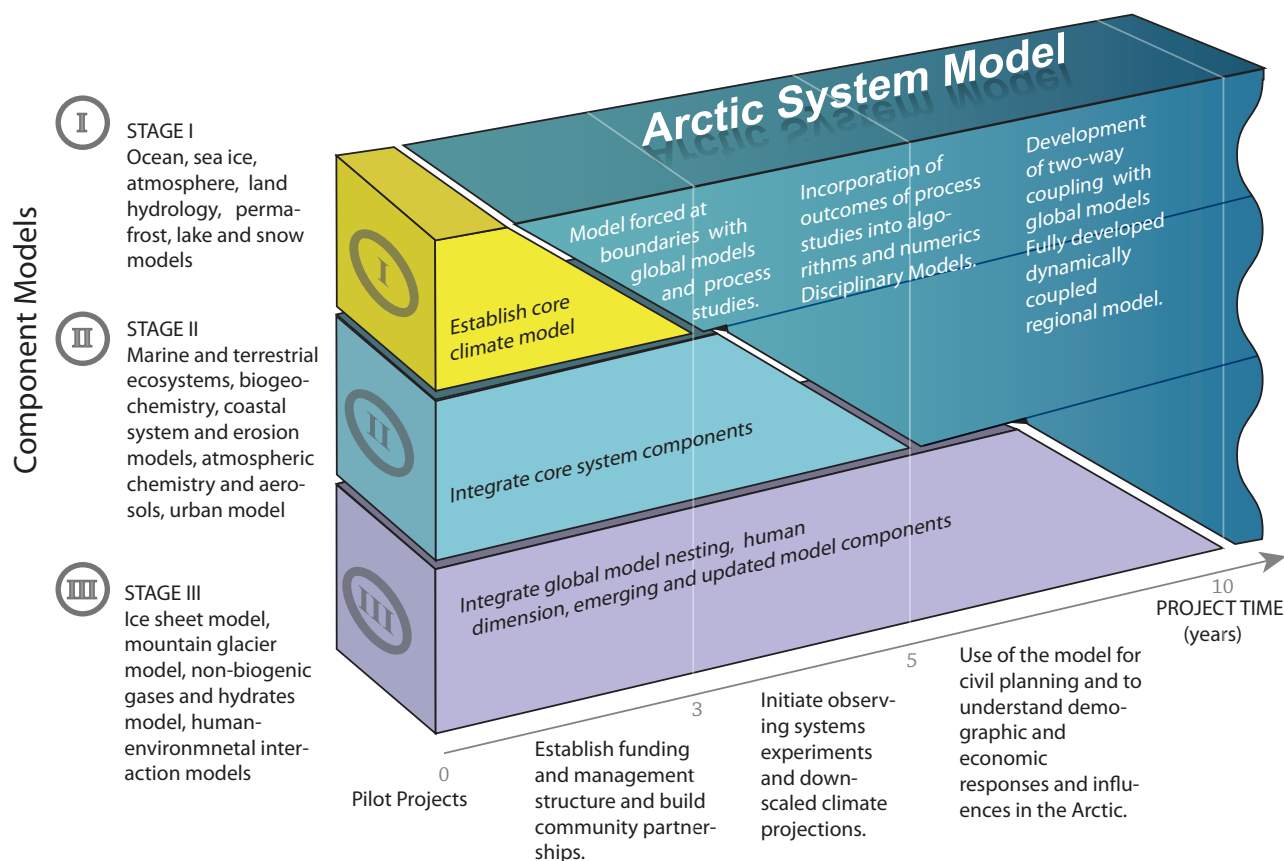


Figure 8: Phased implementation: progressive inclusion of current and emerging model components into an Arctic System Model (from Roberts et al., 2010).

VISION AND DESCRIPTION

Stage One model development will most likely use global model output for regional model boundary conditions without interactively nesting candidate ASM models inside global model counterparts. Interactive nesting with a global model will be established at a later date, but this need not delay implementation in subsequent phases of the suggested ASM work plan (Figure 8). Some physical climate components (for example, ice sheet and mountain glacier models) are currently in a low state of readiness for coupling, but these can be included in the regional climate model core at an appropriate time in the future. This work should be conducted in close consultation with existing government laboratories and universities providing components of the physical ASM core.

Stage Two of the ASM program will incorporate coupled “system” biogeochemical and ecological components into the core model. Work for Stage Two can commence

as soon as it has been decided which core climate model components and coupler are to be used. This will ensure that once the first stable regional climate core of the ASM is released, there can be a fast transition to “system model” integrations: simulations including ecosystems, biogeochemistry, coastal erosion, urban effects, and atmospheric chemistry and aerosols (Figure 8).

Stage Three involves the coupling of components least ready for integration into an ASM. This will include regional climate components, such as an ice sheet module, in addition to broader system components including a non-biogenic gases model. Most notably, Stage Three will require the interactive coupling of human-dimension components. These include a wide swath of civil planning modules that can feed back to alter the physical and biogeochemical systems involved. The human-dimension is the least ready of all components for integration into an ASM, and therefore it is

suggested that Stage Three be seeded with its own pilot projects and case studies targeting, for example: rural energy use, relations between dynamic vegetation, caribou energetics and subsistence, and associations between the Bering Sea ecosystem, fisheries, and regional economics.

Each stage of the program requires strong interaction between ASM model developers and the global modeling and observational community, and each is focused on creating a tool to answer the key science questions articulated earlier in this report. Interaction with the global modeling communities is a necessity if interactive global model coupling is to be a success. Rapid progress in Stage One of the ASM program would assist design of the Arctic Observing Network, just as improved arctic monitoring would hasten model development for Stage Two and Stage Three. A more specific discussion of the development timeline occurs later in this report.

NATIONAL AND INTERNATIONAL INVESTMENT

We suggest that the ASM program should have a three-part budget strategy, which leverages other funding of modeling activities relevant to the Arctic:

1. The core science support and coordination functions (Figure 7) should have funding on the order of \$1 million per year focused on support for two resident modelers, a data coordinator, a software engineer, and two visiting scientists who will drive forward model development and observation synthesis and be a point of contact for PI-driven research. Part-time funding should go to the chair of the Scientific Steering Committee, leaders of each of the three working groups, and an administrative assistant.
2. There should be a competitive tender process to provide a primary supercomputing facility for the ASM. The facility would provide computing time to research groups contributing to the ASM program, without them having to pay for this service through their own research grants. We suggest that, in the pilot stage, 2 million computing hours should be made available for the program.
3. Competitive regional arctic modeling PI-driven projects, supported by various agencies, should be assessed partly on their ability to feed into ASM activities in targeted solicitations. Successful candidate proposals should be funded as part of business-as-usual agency funding. However, these grants should be awarded on the condition that the proposed work will contribute to the ASM program and have a strong likelihood of resulting in lasting model improvements. Researchers awarded these grants will be expected to contribute to at least two of the working groups, related workshops, and documentation of the model and its open-source code.

IMPLEMENTATION TIMELINE

A timeline for the ASM program is summarized in Figure 8, and a more detailed explanation is provided here.

Short-term Objectives (years 0–3)

Short-term objectives are those that are likely attainable within three years. They are listed in two categories: projects that can take place before significant funding is obtained, and those that will begin once funding is available.

Short-term objectives toward which work can begin prior to the availability of significant funding:

- Continue ongoing research activities pertinent to ASM development.
- Create an ASM Scientific Steering Committee.
- Establish international partnerships.
- Develop an ASM implementation plan with broad community input.
- Acceptance and support of ASM implementation plan by funding agencies.
- Call for proposals for ASM development released by funding agencies

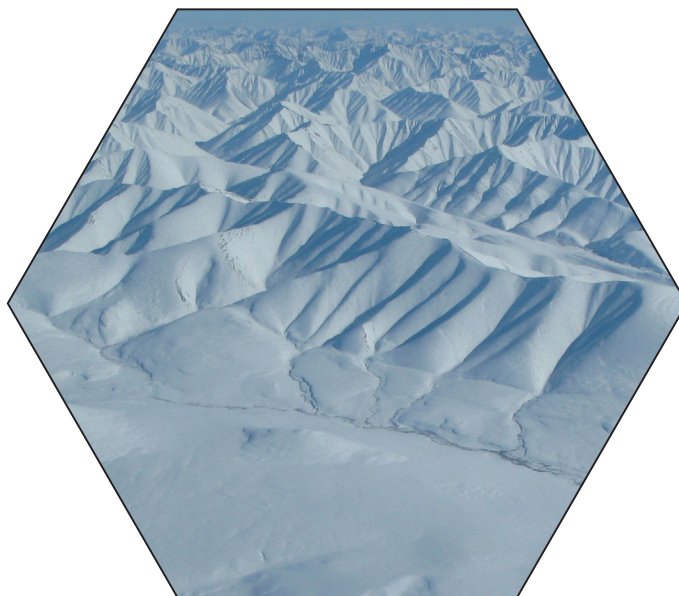
Work on several of these short-term objectives has already begun. Under currently funded projects, progress has been made on the development of a core ASM that includes atmosphere, ocean, sea ice, and land component models. This science plan evolved as a result of three ASM workshops in Alaska, Colorado, and Quebec during and subsequent to the International Polar

Year 2007–2009. The workshops have galvanized a core ASM community and have entrained both national and international partners. It is hoped that this science plan will provide sufficient guidance for eventual announcements of opportunity for ASM development.

Short-term objectives toward which work can begin once funding for an ASM is available:

- Establish management infrastructure and support services.
- Establish a core ASM.
- Launch pilot projects aimed at early successes.
- Incorporate ancillary thematic modelers into ASM activity.
- Develop and incorporate additional component models.
- Integrate observational activities with process studies to improve models.
- Initiate a central support test bed to facilitate verification, validation, and code sharing.

Once funding for a dedicated ASM effort becomes available, rapid progress can be made toward meeting the goals outlined in this report. Key to that rapid progress will be the establishment of a management infrastructure that will facilitate coordination among ASM participants and will provide support services, such as software engineering. It is expected that a core ASM will be completed by the time funding for a coordinated ASM effort is available, or shortly thereafter. Initial scientific objectives, as outlined in the phased implementation section of this report, will be able to take advantage of the newly developed core ASM and should provide early successes and visibility for the ASM effort. Meanwhile, development and incorporation of additional component models into the core ASM will proceed. All components of the ASM should be continually improved through careful model evaluation with available observations and process studies.



Mid-term Objectives (years 3–5)

Mid-term objectives that can be pursued once a core ASM is established:

- Ongoing implementation of new component models.
- Implementation of nesting capabilities of core ASM components within global models.
- Uncoupled (off-line) forcing of emergent component models.
- Initiation of observing system experiments.

Objectives for the mid-term timeframe (3–5 years) will include the ongoing implementation of new component models, including biogeochemical and ecosystem

components and others, depending on their state of readiness. Downscaled projections of Arctic System behavior will be made using standard future scenarios from the IPCC and driven by global climate system model output. Uncoupled (off-line) simulations of emergent component models, such as a coastal erosion module, with forcing from the ASM downscaling runs, will be performed. These simulations will assess the readiness of these components for

coupling to the ASM and provide insight into their future arctic behavior. Nesting capabilities for the core ASM components within global models will be implemented and tested, providing further insight into downscaled Arctic System functioning. The mid-term ASM activities will also include observing system experiments that will aid in observing system design and provide a direct link to the arctic observational communities.



Long-term Objectives (years 5–10)

The ultimate goal is to develop a community Arctic System Model that will enable probabilistic predictions of environmental and social responses to climate dynamics and build a community keystone for understanding the Arctic. Reaching that goal may require more than a single decade. In order to achieve reliable predictability, we must conquer the obstacles limiting our quantitative understanding and

modeling capability of all important system components, their interactions, and their related feedback processes. Additionally, computational capabilities must be advanced to the level where all ASM components may be completely nested within global Earth System Model simulations. On the decadal scale, fully coupled models should include processes associated with the human dimension, including demographic

responses and influences, economic analyses, and other key societal variables. Finally, a large-scale validation program of ASM feedback analyses should be completed to allow quantitative assessment of environmental and societal impacts and responses with resulting understanding of the Arctic as a system.

An Arctic System Model will aid understanding of a host of outstanding arctic science questions. Here we focus on just a few of those questions, providing a background to the proof-of-concept regional modeling projects advocated for the pilot phase of the ASM program on page 16 of this report.

1. Arctic Amplification: Local or Global?

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Arctic amplification is a term used to describe the disproportionate warming (or cooling) that occurs in the Arctic relative to a global mean temperature increase (or decrease) observed on the Earth's surface. Recent changes in the Arctic are a matter of great concern due to the impact that rising temperatures can have on the Arctic and on the global climate system. The importance of these consequences brings about rigorous debate concerning the spatio-temporal structure of changes in the Arctic and mechanisms driving these changes. One of the main topics of the debate is whether arctic atmospheric warming is primarily of a local nature or at least partly induced by changes in global circulation patterns.

Why Arctic amplification?

A positive surface albedo (reflectivity) feedback ranks as one of the most important mechanisms for faster warming in the Arctic. In a warming world, one would expect that increased concentrations of greenhouse gases will lead to sea ice melt and retreat of snow cover, which will result in lower albedo and further acceleration of the warming (e.g., Figure 9). This is a natural self-enhancing mechanism based on local surface radiation budget. Numerous studies have demonstrated how and why climate models with the surface albedo feedback produce polar amplification

of global warming. However, even in the absence of any sea ice-albedo or ocean heat transport feedbacks, Global Climate Models (GCMs) show substantial polar amplification in doubling CO₂ experiments (Alexeev et al., 2005). It has been demonstrated that atmospheric heat and water vapor transport feedbacks play an important role in forming polar amplified response in addition to 'local' albedo feedbacks (Langen and Alexeev, 2007).

Global-Arctic connection

Following is an abridged list of physical mechanisms in the Arctic that can influence the Earth's climate:

- Arctic warming is a part of global warming, but it feeds back on the global scale through mechanisms associated with changes in the reflectivity, or albedo, of clouds and features on the Earth's surface.
- Most glacier ice is located in the polar areas, particularly Greenland and Antarctica. Glacier ice is not like usual sea ice, the freezing or melting of which does not change the sea level. Glacial melt will lead to global sea level rise without regard to political boundaries.
- Glacial melt will affect oceanic thermohaline circulation by dumping vast amounts of water into areas of deep convection near Greenland, with potential catastrophic consequences for global climate.
- Changes in surface properties (disappearance of sea ice and snow and changing vegetation)

will have an effect on atmospheric circulation on the global scale.

- Disappearance of perennial sea ice and switching to a seasonal ice cover can potentially change the Arctic Ocean's stratification with implications for the global thermohaline circulation.

How does a remote climatic signal propagate to the Arctic?

The Arctic has two main pathways for communicating with the rest of the globe: the atmosphere and the ocean. Both are of paramount importance to the energetics of the arctic climate system, but here discussion is limited to the atmosphere.

Vertical structure of the arctic atmosphere is shaped by a strongly negative surface radiation balance, often resulting in sharp surface-based temperature inversions and poleward heat and moisture advection in the troposphere. The heat balance is maintained through meridional heat transport from lower latitudes. The vertical structure of this heat advection controls vertical moisture and temperature profiles and therefore vertical heat exchange and optical properties of the atmosphere, including clouds. Turbulent heat fluxes along with radiation form the net surface heat budget. More heat transport from the lower latitudes will lead to a warmer arctic atmosphere, an increase in the downwelling longwave radiation, and a decrease in the turbulent fluxes at the surface. Cloud changes will also play a big role. Studying processes controlling

the atmospheric heat transports and their interaction with surface conditions is a key to answering questions about atmospheric mechanisms of arctic amplification.

Science questions to be answered:

- What is the response in the Arctic to remote forcings and their importance compared to local mechanisms?
- How 'local' are some of the arctic mechanisms?

An Arctic System Model will serve as an ideal vehicle for conducting a set of experiments to study

the nature of arctic amplification. One advantage of a regional climate model over a global model is greater flexibility in experimenting with lateral boundary forcing in both the atmosphere and the ocean. By prescribing various atmospheric boundary conditions, we can study responses in the Arctic to moisture and heat transports with different properties. Various components of the response of the arctic atmosphere to changing lateral boundary and surface conditions can be investigated. These components include clouds, vertical stratification, radia-

tive properties of the atmosphere, and short- and long-term changes at the surface (sea ice, snow, permafrost, vegetation, hydrology). The possibility of switching the model design from one-way to two-way coupling can help answer interesting questions about the Arctic-global connection. In addition, high horizontal and vertical resolution, especially in the near-surface atmosphere, will help address issues related to adequate comparison of observed and modeled data.

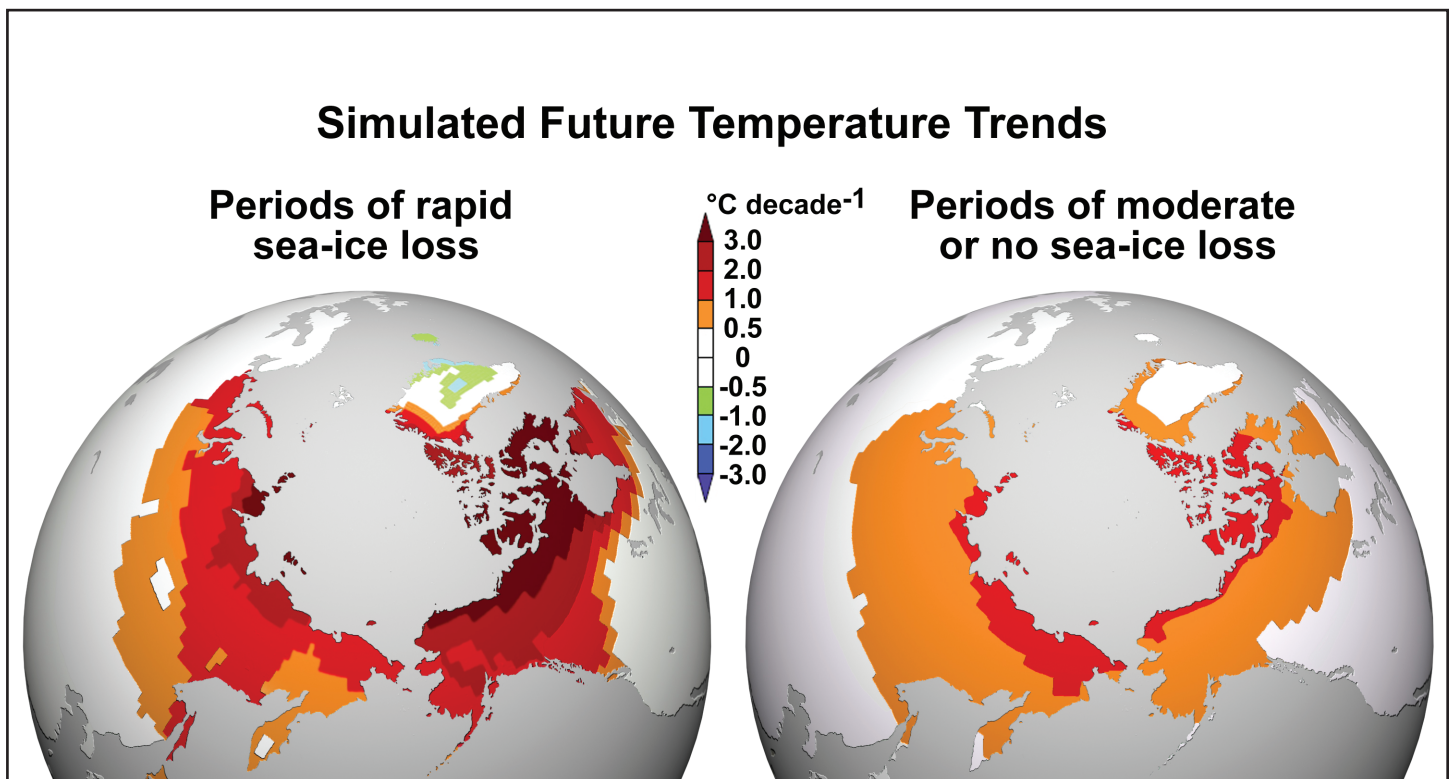


Figure 9: Accelerated arctic warming related to sea ice loss. Simulations by global climate models show that when sea ice is in rapid decline, the rate of predicted arctic warming over land can more than triple. The image at left shows simulated autumn temperature trends during periods of rapid sea ice loss, which can last for 5 to 10 years. The accelerated warming signal (ranging from red to dark red) reaches nearly 1,000 miles inland. In contrast, the image at right shows the comparatively milder but still substantial warming rates associated with rising amounts of greenhouse gas in the atmosphere and moderate sea ice retreat that is expected during the 21st century. Most other parts of the globe (in white) still experience warming but at a lower rate, less than 0.5 °C per decade. Image by Steve Deyo, ©University Corporation for Atmospheric Research, (adapted from Lawrence et al., 2008).

2. Future Changes in Arctic Sea Ice Cover

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Introduction

Satellite records show a decreasing trend in extent and concentration of arctic sea ice cover since 1979 (Serreze et al., 2007). This trend, superimposed over large seasonal and interannual variability (Comiso et al., 2003), is associated with steadily decreasing volume in sea ice thickness that has been observed (e.g., Rothrock et al., 2003) and can be modeled (Figure 10). This trend accelerates from ~8% per decade when the record is extended through 2005 to over 10% per decade when the record minimum of September 2007 is included. When calculated relative to the long-term mean of 1979–2000, the arctic sea ice extent minimum of 2007 was almost 40% below average. It is important to note that this accelerated melt in the 21st century has occurred under a relatively neutral AO regime (while warming has been typically associated with a high positive AO index),

which poses important questions about the actual role of AO in sea ice variability (Overland and Wang, 2005).

The decreasing sea ice cover, through positive ice-albedo feedback, will lead to further warming of the upper ocean and lower atmosphere, further reductions of sea ice, and subsequent increases of freshwater export into the active convection regions in the North Atlantic. Such changes may have major consequences on the ocean thermohaline circulation as well as on the long-term global ocean heat and salt transports and climate. If continued, the warming trend will not only significantly affect global climate, but also change the strategic and economic importance of the Arctic Ocean through increased commercial shipping routes and access to natural resources. According to some model results, we can expect near ice-free September conditions by 2050; an ice-free Arctic Ocean is typically defined as having less than 1 million km² of sea ice coverage (Stroeve et al., 2007; Wang and Overland, 2009; Figure 11).

However, details of variability in the total sea ice volume, its causes and effects on lower latitudes, are not fully understood and require knowledge of the operation of the coupled Arctic System. The main issue is that global climate models are critically limited in representing the Arctic. They need improved representation of interactions and feedbacks among ASM components to advance understanding and prediction of Arctic System change.

Model requirements

The ocean and sea ice component of the arctic climate system operates on three basic principles. First, it receives the heat and buoyancy fluxes from the atmosphere at the surface and from lower latitude oceans via northward advection of water mass properties. River runoff contributes significant freshwater input locally. Second, the net heat and buoyancy sources together with dynamic wind forcing modulate the state of the sea ice cover, determining variability in multi-year and first-year ice distribution, regions of net growth and melt of sea ice, and the amount of total freshwater

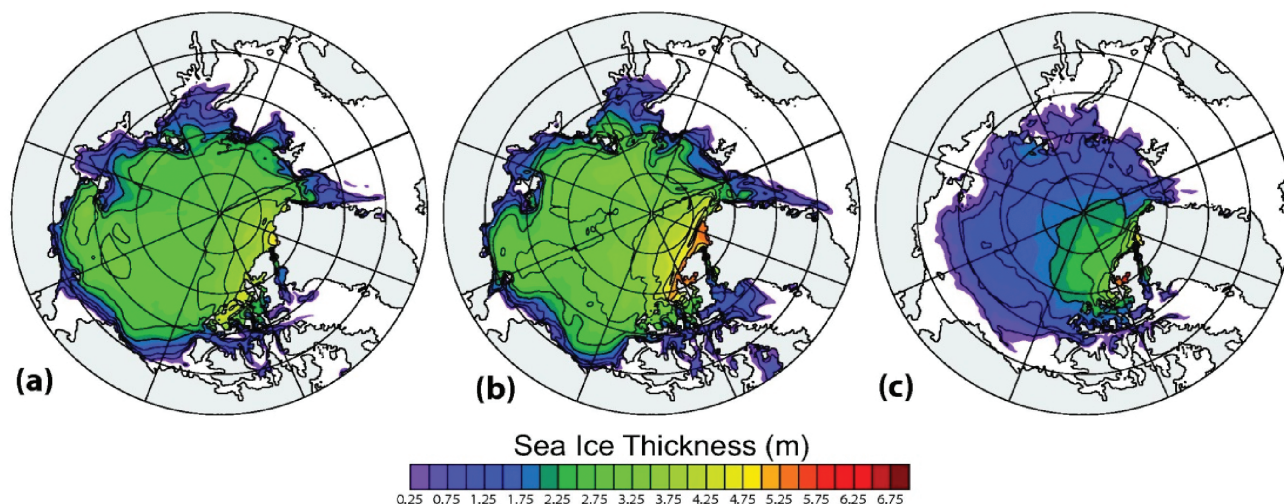


Figure 10: Mean arctic sea ice thickness simulated with the Naval Postgraduate School high-resolution (9km) regional ice-ocean model in September: (a) 1982, (b) 1992, and (c) 2002.

content. Most of the first-year sea ice production takes place locally near the coast and over the shelves where brine rejected from sea ice changes seawater density. This seasonal signal is communicated to the wider arctic basin. Third, the combined effects of wind- and thermohaline-driven circulation redistribute water masses and sea ice within the Arctic Ocean and control their export to the North Atlantic. Most of the freshwa-

ter signal is confined to the coast in the form of buoyancy-driven coastal currents and to the upper water column, as determined via shelf-basin and atmosphere-ice-ocean exchanges.

Recent studies of North Atlantic Deep Water properties suggest a multi-decade freshening trend (Curry and Mauritzen, 2005). Such changes can affect the strength of meridional overturning circulation

in the North Atlantic and long-term global ocean heat and salt redistribution and climate variability through linkages to the ocean thermohaline circulation. Growing evidence based on observations (Belkin et al., 1998) and models (Maslowski et al., 2001) points to the Arctic as the main source of such changes.

It is clear from the above summary that coastal and continental margins and shelf-basin

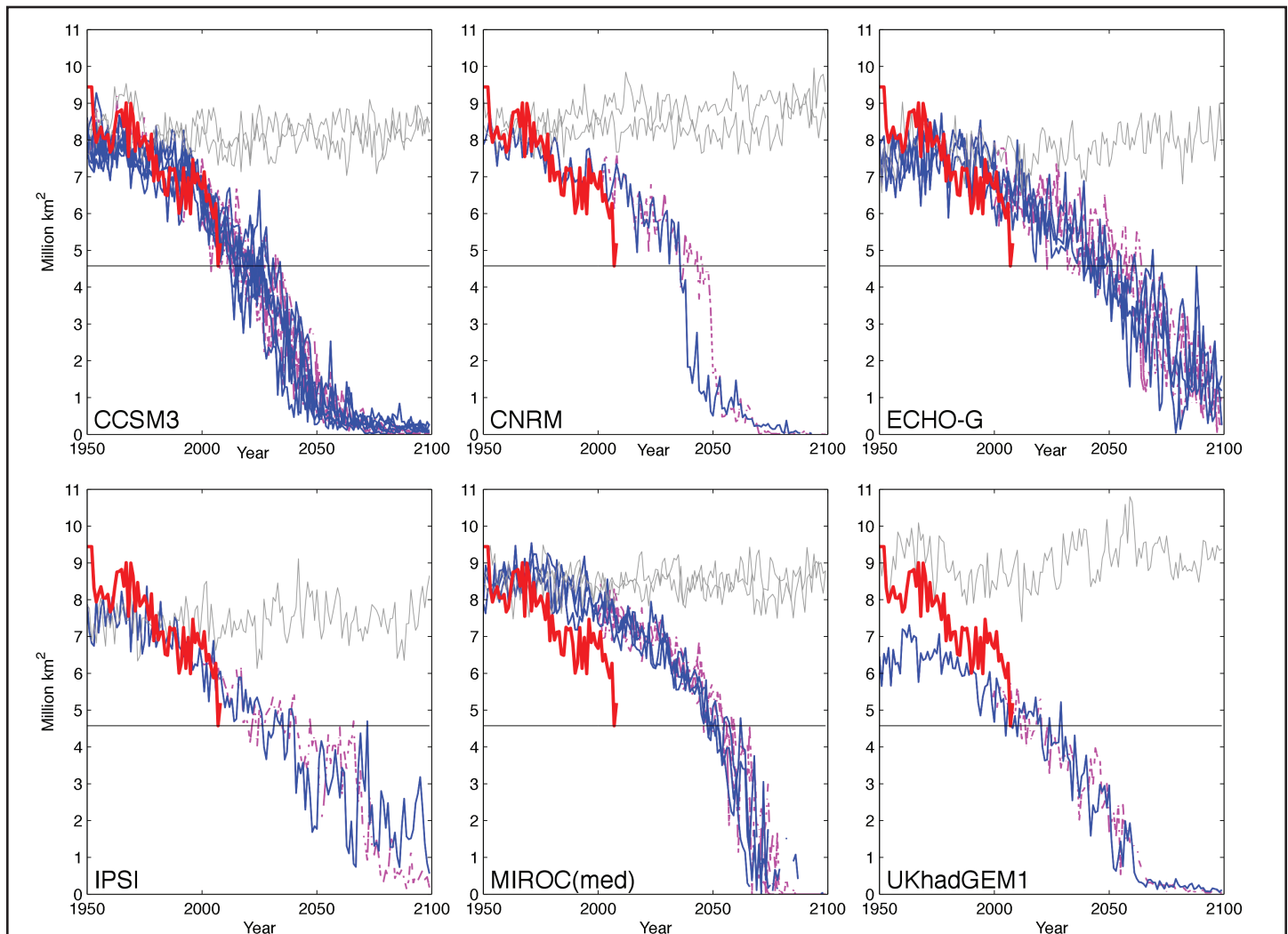


Figure 11: September sea ice extent as projected by the six Intergovernmental Panel on Climate Change (IPCC) models that simulated mean minimum extent and seasonality with less than 20% error from observations. Each panel represents a different model. Thin lines represent ensemble members (realizations) from the same model under IPCC A1B (blue solid) and A2 (magenta dashed) emission scenarios, and the thick red line is observed changes (based on Hadley Center sea ice concentration analysis). Gray lines in each panel indicate the time series from the model runs without anthropogenic forcing for the same model in any given 150-year period. The horizontal black line shows the minimum sea ice extent reached in September 2007. All six models indicate rapid decline in the ice extent to reach an ice-free summer (less than 1 million km²) before the end of the 21st century (from Wang and Overland, 2009).

exchange are critical to the overall circulation of the Arctic Ocean. However, processes controlling those exchanges are not well known from observations, and they have posed great challenges to global ocean and climate models. For example, the advection of oceanic heat northward through Fram Strait remains a problem for most global ocean and climate models. The general tendency in low-resolution models is to transport most Atlantic water into the Arctic Ocean via the Barents Sea and to advect water through Fram Strait to the south only (Oka and Hasumi, 2006). This presents a problem. Most of the heat entering the Barents Sea is lost to the atmosphere (Maslowski et al., 2004) before entering the central Arctic Ocean, which means that oceanic heat input to the eastern Arctic might be significantly under-represented. Similarly, the inflow of Pacific summer water through the narrow (~100 km) and shallow Bering Strait and its circulation over the Chukchi Shelf and in the Beaufort Sea is not realistic in low-resolution models. This creates problems in the western Arctic and has consequences downstream in the North Atlantic (Hu and Meehl, 2005). Another challenge for global climate models is representation of narrow (10–100 km) coastal and boundary currents, which in the Arctic Ocean are main circulation features and eddies that locally control shelf-basin exchange and mixing.

The oceanic heat, in addition to atmospheric radiative and sensible heat input, contributes to sea ice melt, which in recent years has accelerated, especially in regions directly downstream of oceanic heat advection from the Pacific and Atlantic oceans (Stroeve and Maslowski, 2007). Recent reduction of the arctic ice pack has been primarily associated with anomalies of surface air temperature and circulation over the Arctic, as suggested by the studies of Rigor et al. (2002) and Francis et al. (2005). Such studies focus on the role of external atmospheric forcing, but internal Arctic Ocean processes also play a role. Oceanic thermodynamic control of sea ice through the under-ice ablation and lateral melt along marginal ice zones is especially overlooked. However, these ice-ocean interactions may act to de-correlate AO forcing, which could help explain some of the timing issues between atmospheric forcing and sea ice variability.

Basic ocean dynamics and circulation in the Arctic Ocean are difficult to parameterize for use in low-resolution global ocean and climate models. Some of the most important features that need improved representation in climate models include heat advection into and within the Arctic Ocean, mixing and transport on shelves and into deep basins, sea ice melt, production, distribution, and deformation, and freshwater export into the North Atlantic. All the above phenomena are to some degree controlled by eddies, exchanges through narrow and shallow passages, narrow

boundary and coastal currents, and sea ice conditions. A characteristic spatial scale for these processes is 10–100 km, which implies a grid size of 1–10 km. In addition, vertical resolution of 1–5 m is required for realistic representation of coastal geometry, shelf bathymetry, and water column property distribution.

Needs for an Arctic System Model

Regional atmospheric or ice-ocean models have been developed and successfully implemented in the Arctic, advancing knowledge of the operation of various components of the climate system. However, those efforts have limits in addressing the operation of the fully coupled arctic climate system. They cannot account for important sea-ice-atmosphere feedbacks as they typically either simulate the atmospheric state with prescribed lower boundary conditions for ice-ocean state or predict ice-ocean variability using prescribed atmospheric forcing (Rinke et al., 2006; Maslowski et al., 2004). Global climate models have large errors in representing sea ice distribution, northward fluxes of heat and moisture, and export of fresh water into the North Atlantic. Their realistic representation is critical to improved future climate predictions.

A high-resolution regional ASM including state-of-the-art land, atmosphere, sea ice, and ocean components can address the above deficiencies. Such a regional model will advance understanding of past and present states of the Arctic System and will improve prediction of its future regimes and its potential effect on global climate.

Introduction

Most of this storage has accumulated because of wet and cold physical conditions that are not conducive to the decomposition of soil organic matter. Between 10% and 20% of the world's vegetation carbon occurs in the Arctic, mostly as tree biomass in the boreal forests. There are large stocks of Dissolved Inorganic carbon (DIC) in the Arctic Ocean, about 1% of which is derived from fossil fuel emissions that have entered the atmosphere. It is estimated that

substantial stocks of CH_4 are stored as gas hydrate beneath the ocean floor and beneath both subterranean and submarine permafrost of the Arctic, but there is uncertainty about the magnitude of these stocks.

The Arctic plays an important role in the global dynamics of both CO_2 and CH_4 . Top-down atmospheric analyses indicate that the Arctic is a sink for atmospheric CO_2 of between 0 and 0.8 Pg C yr^{-1} (Figure 12), which is between 0% and 25% of the net land/ocean

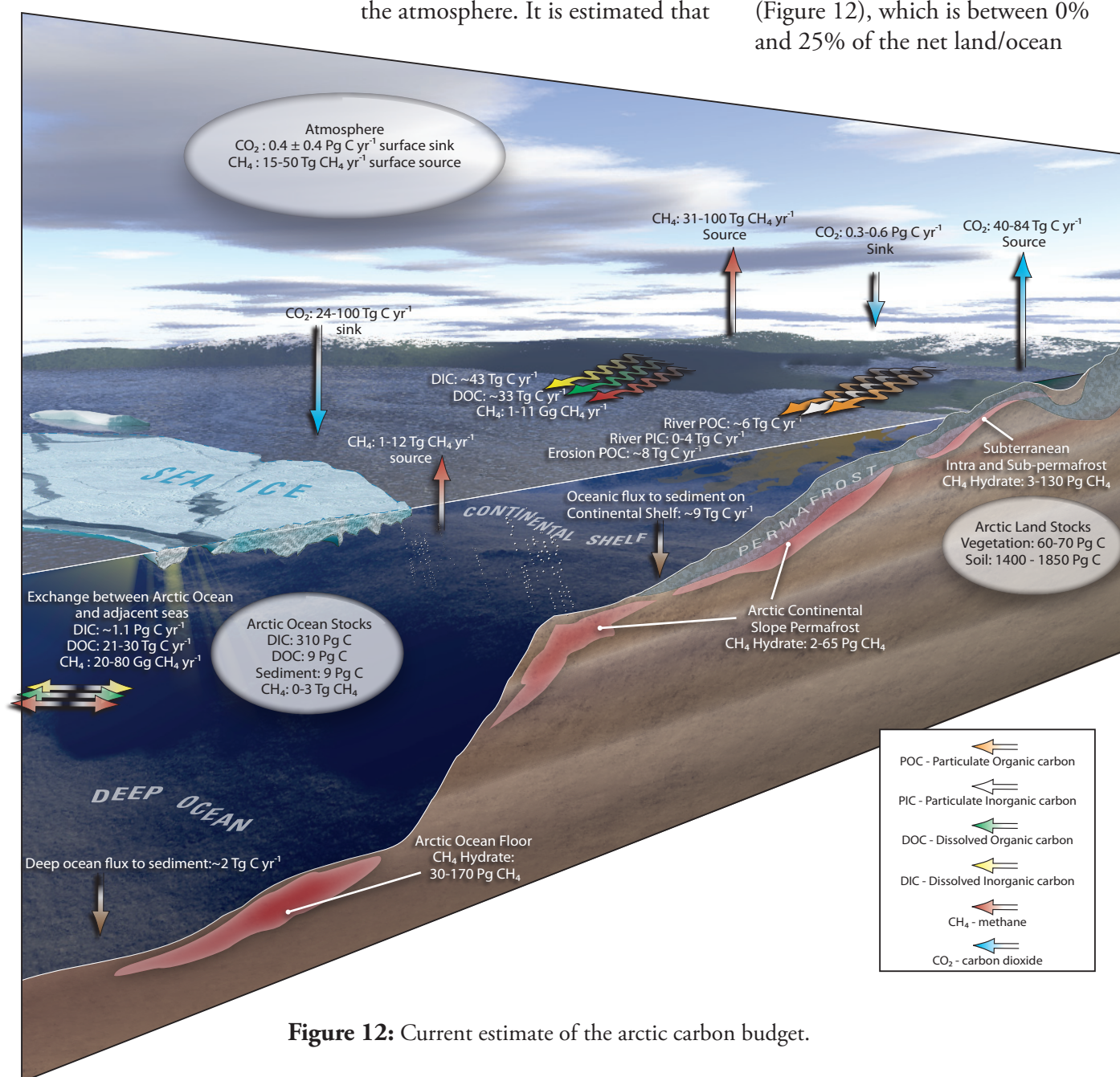


Figure 12: Current estimate of the arctic carbon budget.

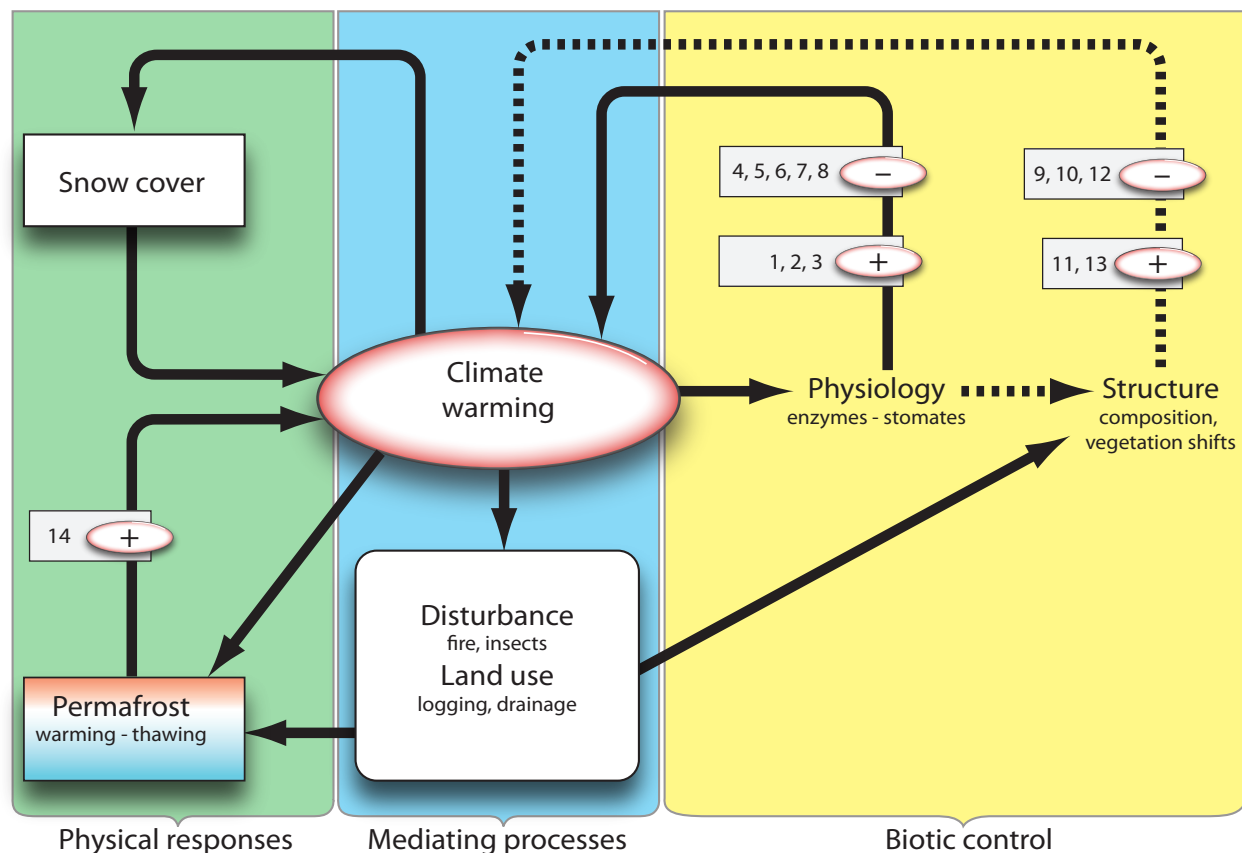
flux of 3.2 Pg C yr⁻¹ estimated for the 1990s by the IPCC's 4th Assessment Report (AR4; Denman et al., 2007). Atmospheric analyses indicate that the Arctic is a source of CH₄ to the atmosphere of between 15 and 50 Tg CH₄ yr⁻¹, which is between 3% and 9% of the net land/ocean source of 552 Tg CH₄ yr⁻¹ (582 Tg CH₄ yr⁻¹ source—30 Tg CH₄ yr⁻¹ soil sink) estimated by AR4 (Denman et al., 2007). Approx-

mately 80 Tg C yr⁻¹ are transferred from land in the Arctic to ocean via rivers (Figure 12), which is about 10% of the estimated 0.8 Pg C yr⁻¹ transferred from land to ocean via rivers globally (Sarmiento and Gruber, 2006).

Simulating the complete carbon cycle

The carbon cycle in the Arctic has the potential to influence the climate system through feedback

pathways involving responses in terrestrial and marine systems (Figure 13 and Figure 14). Processes in terrestrial regions of the Arctic that are sensitive to change on a 10- to 20-year timeframe are those that are primarily sensitive to changes in atmospheric variables (e.g., temperature, precipitation, CO₂ concentration) and include photosynthesis (feedback pathways 2, 5, 6, and 7 in Figure 13) and fire (feedback



Physiological feedbacks designated on the diagram are:

- (1) increased decomposition of soil organic matter (CO₂ ↑),
- (2) vegetation productivity (NPP) response to drought stress (CO₂ ↑),
- (3) methanogenesis response to increasing temperature and soil moisture (CH₄ ↑),
- (4) methanogenesis response to drying (CH₄ ↓),
- (5) NPP response to longer growing season (CO₂ ↓),
- (6) NPP response to increased N mineralization (CO₂ ↓),
- (7) NPP response to temperature increase (CO₂ ↓), and
- (8) NPP response to increased atmospheric CO₂ concentration (CO₂ ↓).

The structural feedbacks shown are:

- (9) expanded distribution of tundra shrubs (CO₂ ↓),
- (10) treeline advance (CO₂ ↓),
- (11) forest degradation (CO₂ ↑),
- (12) conversion of light to dark taiga (CO₂ ↓), and
- (13) increased occurrence of fire, insects, and logging (CO₂ ↑). The physical responses include
- (14) the release of inorganic carbon from permafrost thaw (CO₂ ↑, CH₄ ↑).

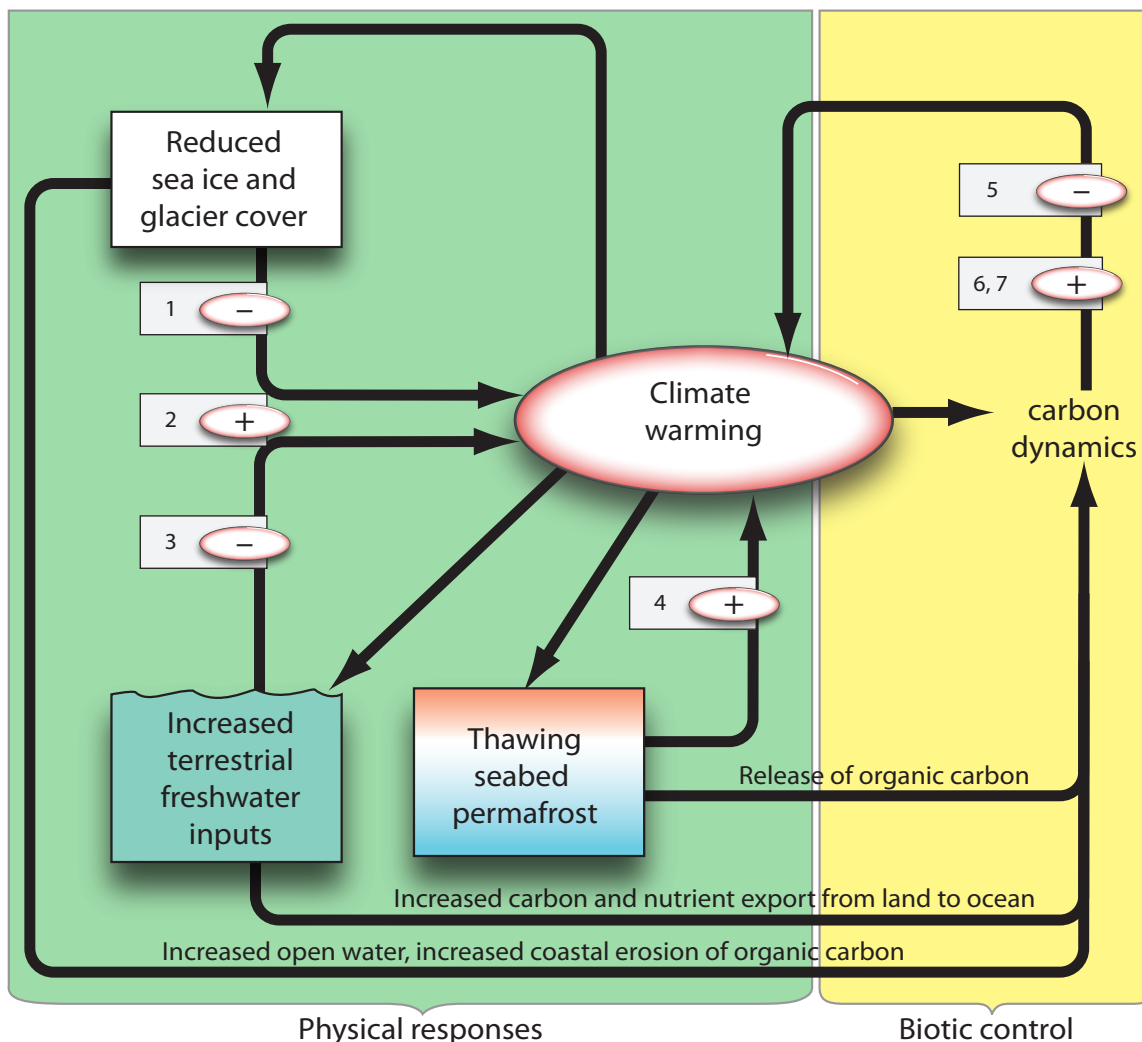
Figure 13: Terrestrial carbon responses and pathways to warming in the Arctic. Physical responses of snow cover and permafrost on the left are coupled with functional (physiological) and structural biotic responses on the right. Modified from McGuire et al. (2006).

pathway 13 in Figure 13). The net direction of the photosynthesis and fire feedbacks depends substantially on landscape wetness and dryness. For example, photosynthesis may be decreased more by dry conditions than it will be promoted by a longer growing season. Also, dry conditions may result in the release of substantial carbon through fire. The

50- to 100-year timeframe involves processes that respond slowly to climate. For terrestrial ecosystems, these include slow ecological processes (e.g., increase in shrub tundra, changes in tree species, treeline advance, and forest degradation) and decomposition responses associated with the thawing of permafrost (Figure 13). Once permafrost thaws,

the direction of feedbacks to the climate system depends largely on landscape wetness and dryness.

For marine systems, processes sensitive to changes in surface conditions like sea ice cover and near surface water temperature could have substantial responses on the 10- to 20-year timeframe. A decreasing sea ice cover could increase CO_2



The physical responses depicted on the diagram are:

- (1) increased CO_2 solubility in response to more open water and lower salinity ($\text{CO}_2 \downarrow$),
- (2) decreases CO_2 solubility with increasing temperature ($\text{CO}_2 \uparrow$),
- (3) the burial of organic C in deep ocean sediments ($\text{CO}_2 \downarrow$), and
- (4) the release of inorganic carbon from sediments, ocean floor, and submerged permafrost ($\text{CO}_2 \uparrow$, $\text{CH}_4 \uparrow$).

The biotic feedbacks include:

- (5) biotic productivity response to increased light and nutrients ($\text{CO}_2 \downarrow$),
- (6) stable photic zone ($\text{CO}_2 \uparrow$), and
- (7) warming induced increases in decomposition and methanogenesis ($\text{CO}_2 \uparrow$, $\text{CH}_4 \uparrow$).

Figure 14: Marine carbon responses and pathways to warming in the Arctic that influence the climate system. Responses of sea ice, glaciers, and seabed permafrost (on the left) are coupled with biotic responses (on the right) through several mechanisms affecting carbon dynamics. Modified from McGuire et al. (2006).

sequestration through increasing the physical transfer of DIC to the surface layer (feedback 1 in Figure 14) and the biological uptake of CO₂ in the surface layer through more light and nutrients (feedback 5 in Figure 14), but could decrease CO₂ uptake through the creation of a stable photic zone (feedback 6 in Figure 14). In contrast, increases in water temperature also have the potential to enhance the release of CO₂ and CH₄ through enhanced decomposition and methanogenesis of organic carbon in the water column (feedback 7 in Figure 14).

The release of free inorganic CO₂ and CH₄ frozen in terrestrial soils and marine sediments and the dissolution of CH₄ from gas hydrates (feedback pathways 14 in Figure 13 and 4 in Figure 14) as a result of permafrost thaw are likely to proceed at a very slow pace. While there is uncertainty about the degree to which near surface permafrost will

thaw, the thawing of permafrost at depth from the transfer of heat from the overlying atmosphere is likely to be a millennial-scale response. This disappearance of thick permafrost is most likely to occur in settings where the ice content of permafrost is high and the vertical structure of permafrost is exposed to the atmosphere and erosional runoff (e.g., along river banks). Clearly, it remains a major challenge for the scientific community to represent how climate change will influence the release of CH₄ from hydrates in both terrestrial and marine systems of the Arctic (Corell et al., 2008).

Summary

Coupled carbon-climate models do not currently consider several carbon cycle issues that are important in the dynamics of terrestrial ecosystems in the Arctic:

1. How mosses and organic soils influence soil thermal and hydrologic dynamics.

2. How hydrologic responses influence the extent of wetlands and the position of the water table within wetlands to influence carbon dynamics of wetland ecosystems.

3. How interactions among plant functional types of ecosystems in the Arctic influence carbon storage.

4. How interactions between carbon and nitrogen dynamics influence carbon storage.

Similarly, coupled carbon-climate models do not currently consider several issues that may be important to the responses of the carbon cycle in marine systems of the Arctic:

1. The effects of sea ice changes on the solubility and biological pumps for CO₂ uptake.
2. The dynamic coupling of terrestrial and marine carbon.
3. The response of seabed permafrost and its effects on carbon stored in seabed permafrost

4. Processes Affecting Glacier Mass Balance

Anthony Arendt, Regine Hock, Martin Truffer, John Walsh, and Uma Bhatt - University of Alaska Fairbanks

Introduction

Glaciers and ice sheets store a significant fraction of the Earth's fresh water, and their changes affect arctic hydrology, ocean circulation and height, and crustal uplift rates. Glaciers and ice sheets are presently responsible for about one-half of the rate of rising global sea level, and they have the potential for larger contributions if accelerated warming of polar regions continues (ACIA, 2005).

The Arctic contains a large fraction of the Earth's land ice, and includes the Greenland ice sheet, as well as mountain glaciers and

ice caps (MG&IC) of the Canadian Arctic Archipelago, Alaska, northwestern Canada, Spitzbergen, Iceland, and the Russian Arctic. The Greenland ice sheet has the largest area and volume of arctic land ice, and is the largest potential contributor to rising sea level. However, on a global scale, MG&IC presently contribute more fresh water to the oceans than the two major ice sheets, and may continue to be the dominant contributor to changes in sea level related to the cryosphere for the next 50–100 years (Meier et al., 2007).

For many years, the study of land ice evolution has focused on estimating glacier melting and accumulation (the surface mass balance) in response to changes in climate.

While the surface balance is often a large component of the overall glacier mass budget, recent work has highlighted the potential for rapid changes resulting from dynamic instabilities where ice masses terminate in the ocean or in lakes. Drivers for these dynamic mass losses are poorly understood. Increasing ocean temperatures causing enhanced melting at the glacier calving front, as well as enhanced lubrication of the glacier bed in response to increases in the flux of surface meltwater, are likely contributors. A rapid increase in velocity of numerous large outlet glaciers of the Greenland ice sheet highlights the role of dynamic changes in determining the ice sheet's total mass loss (Rignot and Kanagaratnam, 2006). Dynamics

also play an important role in the mass budget of MG&IC tidewater glaciers located in maritime environments (Pfeffer, 2003).

Previous Modeling Efforts and Challenges

Increasing evidence of the feedbacks between atmosphere, ice, and ocean systems highlights the need for an integrated modeling approach. This work has been started for the ice sheets via two-way coupled thermo-mechanical ice sheet and atmosphere-ocean general circulation models (AOGCM; e.g., Fichefet et al, 2003). The primary limitation of these models is one of spatial resolution, as existing AOGCMs must be downscaled to provide sufficient detail to drive the glacier model. In addition, the maximum resolution of existing ice sheet models is about 5 km, which is insufficient for resolving outlet glaciers, where many of the important dynamic changes are occurring. Furthermore, continental scale ice sheet models usually solve low order approximations of the flow equations, which are not appropriate for outlet glaciers. Similar scaling issues limit detailed modeling of MG&IC, many of which have dimensions of 0.1–10 km, far below the resolution capabilities of global climate models. Bhatt et al. (2007) “telescoped” a regional model to focus on the glaciated region of southeastern Alaska (Figure 15), using high-resolution model-derived forcing to drive a mass-balance model for various glaciers, most of which have been retreating (e.g., Bering Glacier) but a few of which have been growing (e.g., Hubbard Glacier). The global model output was obtained from the CCSM. The results of simulations of past and future mass balances suggest that the Bering Glacier will lose significant

mass and that Hubbard Glacier will grow more slowly in the near future than in the recent past. Hock et al. (2009) used gridded climate reanalysis and glacier extent data together with modeled glacier sensitivities to estimate the global contribution of MG&IC to rising sea level during the past 50 years. The uncertainty in their estimates was largely a result of limited glacier inventory data as well as sparse mass balance measurements for the calibration of their sensitivity models. These models do not attempt to simulate the flow of the ice, but concentrate on the surface mass balance.

A common thread emerges from existing work concerning limitations of existing modeling approaches.

The first is that existing AOGCM and climate reanalysis model output are too coarse to resolve the detailed processes in atmosphere and ocean dynamics that are presently driving glacier and ice sheet changes. The second is that the dynamic processes affecting ocean-terminating ice are poorly understood and suffer from important data gaps, particularly with regard to basal topography. They have yet to be quantified on a global scale and are not adequately accounted for in regional scale glacier and ice sheet models. A third problem unique to MG&ICs is the lack of an inventory of ice extent and elevation distribution necessary to provide the starting condition of any modeling effort.

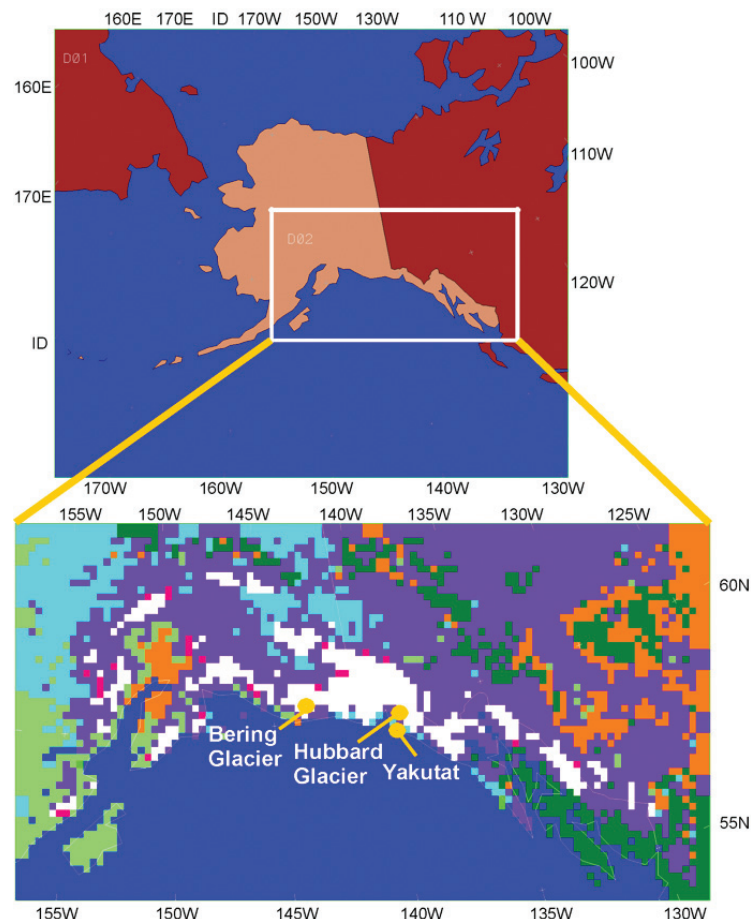


Figure 15: Outer domain (D01, upper) and nested high-resolution inner grid (D02) of Mesoscale Model 5 (MM5) simulations by Bhatt et al. (2007) used to downscale information from a global model for glacial studies.

Data Requirements and Framework of an ASM for Arctic Glaciers and Ice Sheets

An Arctic System Model, with its focus on the interaction of multiple components of the Arctic System, is an ideal framework within which issues identified above can be addressed. In addition, there are a number of observational data gaps that must be filled. The first challenge is to develop a complete inventory of MG&IC extent, size, and elevation distribution for arctic glaciers. This is easily achieved given the availability of optical satellite imagery, but few research programs are willing to dedicate funds to the task. Second, the loss of ice mass by iceberg calving must be estimated for all arctic glaciers and ice caps to quantify the proportion of mass losses that occur due to dynamic versus surface mass balances. Mapping the total length of ice calving fronts and estimating the depth of the fjord into which the ice is deposited may achieve this. A

third data gap concerns the lack of climate measurements in polar and alpine regions necessary for the validation of GCM and reanalysis model output, and the calibration of glacier/mass balance models. Finally, data on basal topography is crucial for estimating existing ice volumes as well as for providing important input data for flow models. All of these data can be combined in a way that maximizes their particular strengths, providing a more robust set of validation datasets for the development of an ASM.

A key challenge associated with system models is the need to resolve the elevation-dependence of the primary forcing fields, temperature and precipitation, including the elevation of the freezing temperature and the rain/snow boundary. One approach that has been used to achieve the required resolution of forcing data is to dynamically downscale global model output by use of a regional atmos-

pheric model, illustrated in Figure 15. Bhatt et al. (2007) used down-scaled atmospheric model output to drive a glacier mass balance model without feedbacks between the two models. Because glaciers and ice sheets affect the local atmospheric environment, the future challenge is to couple models of glaciers and ice sheets with other components of the Arctic System, including the upper ocean where effects of changing freshwater discharge will be felt. In addition, formulations of ice sheet dynamics must be enhanced in order to capture the effects of ice flow and calving. The lack of sufficiently robust projections of Greenland's calving rates was widely cited as a limitation of the recent IPCC estimates of projected changes in sea level. Coupled simulations that capture interactions between climate (atmosphere and oceans), ice sheets (Greenland), and glaciers represent some of the potentially most consequential applications of an ASM.

5. Arctic Coastal Erosion Along the Beaufort Sea, Alaska

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Hugues Lantuit and
Pier Paul Overduin—Alfred Wegener
Institute for Polar and Marine Research

The presence of ice, perennially in the ground and seasonally on the arctic sea margins, distinguishes arctic coastal dynamics from those in temperate or tropical coastal zones. Coastal erosion is favored by large amounts of ground ice and silt sediments in the unconsolidated permafrost shorelines, and the coastal bluff is affected by thermo-erosion. The overall effect of permafrost coastlines is a higher erosion rate than observed at temperate (permafrost-free) latitudes (Are et al., 2008). Along

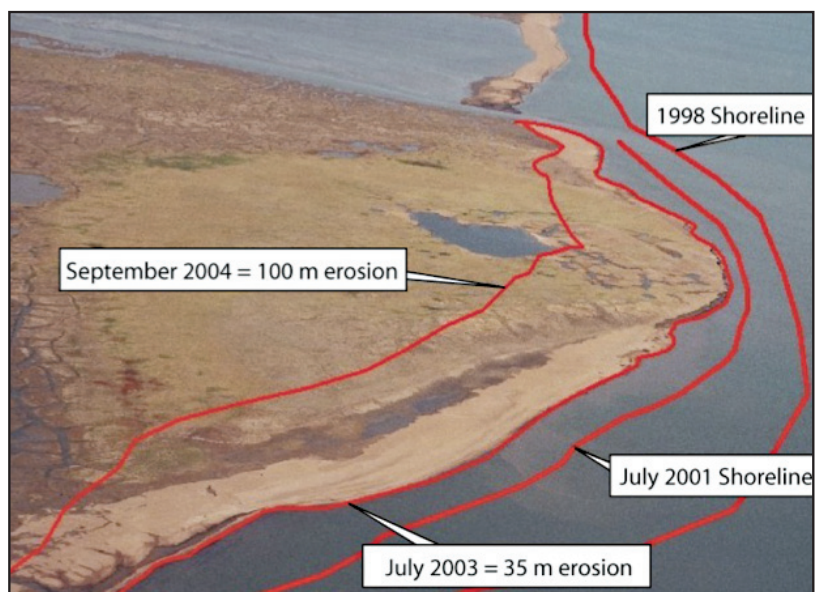


Figure 16: Coastal retreat near Drew Point, Alaska, is up to 100m in 1 month (photo courtesy of Susan Flora, Bureau of Land Management).

arctic coastlines, sea ice, permafrost, and shoreface morphology are linked in the nearshore zone, making the system particularly sensitive to changes in climate.

The Alaskan Beaufort Sea coast has been rapidly eroding over the last decade, highlighting the susceptibility of arctic shorelines to changes in climate (Jorgenson and Brown, 2005). As an example, the northeastern coast of the National Petroleum Reserve at Drew Point, Alaska, shows coastal erosion rates locally exceeding 100 meters per year, demonstrated in Figure 16 and Figure 17. Local infrastructure related to petroleum exploration and national security is at risk of being lost to the ocean. These values exceed the upper ranges of previously estimated arctic coastline erosion rates, suggesting that the trajectory of change in the Alaskan Beaufort Sea coastal zone is toward higher local erosion rates. Recent studies dealing with other parts of the Arctic have highlighted the lack of reliable trends over the past fifty to sixty years (Lantuit and Pollard, 2008; Lantuit,

2008). Variability in local or regional forcing factors seems to dominate over increases in storminess.

However, Mars and Houseknecht (2007) studied satellite imagery and topographic maps and showed that coastal erosion rates regionally doubled over the last fifty years. This period of increased coastal change coincides with a decline in sea ice extent, which inevitably exposes arctic coastlines to increasing wave attack. It is remarkable, though, that major retreat events in this region, as elsewhere in the Arctic, do not necessarily coincide with the occurrence of ocean storms (Lantuit, 2008). A correlation between rapid coastline retreat and warming ground and sea temperatures also implicates a reduction in the resistance of coastal bluffs to wave attack, and an increase in the rates of melting along permafrost-affected arctic coastal bluffs. Thermokarst events have also been shown to alter the shore profile in a dramatic manner. Rivers bringing in warm fresh water may further enhance rapid melting in

their immediate proximity. Another localized effect is that the breaching of thaw lakes is accelerating, and this rapidly changes the local hydrology and affects terrestrial ecosystems.

Numerous studies quantify rates of shoreline retreat Arctic-wide (Hume and Schalk, 1967; Harper, 1978; Lantuit and Pollard, 2008; Mars and Houseknecht, 2007). However, environmental drivers such as sea ice, sea surface temperatures, wind and wave energy, thermal energy, coastal substrate properties, and inputs of water and sediment from fluvial systems are not comprehensively monitored or modeled. Traditional engineering models of coastal evolution do not deal with the complications of storms dampened by sea ice or a melting substrate that is eroded. An integrated approach involving climate scientists, oceanographers, physical geographers, and hydrologists will be needed to quantify the processes driving high-latitude coastal landscape evolution. These different science communities must work together to formulate and test

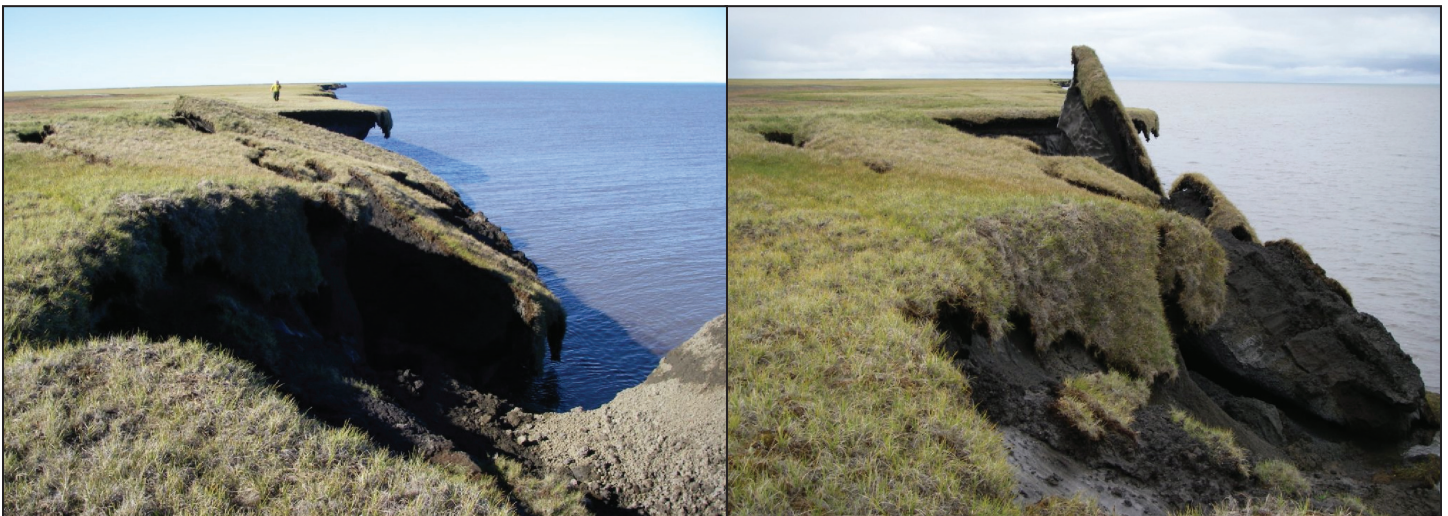
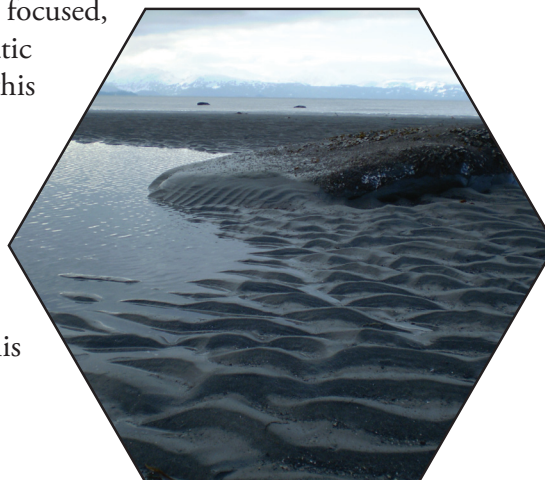


Figure 17: Coastal bluffs near Drew Point, Alaska, eroding over the anomalously warm summer of 2007. The left photo is taken on August 9, 2007, whereas the right photo shows the same location on August 14, 2007 (photos courtesy of Cameron Wobus, Cooperative Institute for Research in Environmental Sciences, University of Colorado).

physics-based models that predict the response of the coast to climatic change. There is a great need to make localized predictions for unique stretches of coast that are vulnerable to erosion because of human settlements or infrastructure or the loss of precious wetland habitat.

It is a challenge to develop a coupled system model that would help to predict where future coastal

erosion is likely to be focused, what particular climatic conditions promote this erosion, and what feedbacks either accelerate or decelerate rates of shoreline change. But the environmental and economic need for this is upon us.



6. Biosphere Feedbacks on Atmospheric Composition and Climate

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Introduction

Incorporating a fully interactive ocean ice ecosystem model into an ASM is essential if we wish to understand how climate change (particularly sea ice decline) will affect the primary productivity of the Arctic Ocean, and how change in the ecosystem will in turn affect arctic climate. Arctic observational networks and field campaigns (many integrated with modeling studies) are making progress toward understanding the past and present state of Arctic Ocean productivity and the interactions of the arctic marine food web with biogeochemical cycles. An ASM would bring together these observations with efforts to model Arctic Ocean and atmospheric circulation, sea ice, terrestrial linkages, atmospheric composition, and marine ecosystems.

Marginal Ice Zones (MIZ) are among the most productive ocean regions. They include the world-class fisheries of the Bering and Barents

seas. It is in the seasonal sea ice zone, which bounds the shifting MIZ, that some of the rapid changes being observed in the Arctic—greater fraction of first-year ice, thinner ice, and reduction in summer sea ice extent—are most evident.

Simulating the effects of sea ice loss on marine ecosystems

The consequences of diminishing sea ice extend well beyond loss of habitat for ice-dwelling organisms (Figure 18). For example, changes in ice cover impact vertical mixing and stratification, influencing nutrient availability in the water column and food sources for benthic communities long after the ice is gone. Sea ice also modulates the air-sea exchange of climate-relevant trace gases and plays important roles in the transport and export of carbon. This occurs, for example, through the ventilation of the deep basins by dense, brine-enriched shelf waters associated with organic and inorganic carbon. Sea ice may also function as a wintertime repository of iron (Fe) (from atmosphere and sediments) made available upon spring ice melt to phytoplankton. All these

are relatively small-scale processes currently not adequately resolved in climate models.

Numerous ecosystem-climate feedbacks have been hypothesized, including biological impacts on atmospheric CO₂, methane reservoirs in ocean sediments, carbon export-Fe input, and dimethylsulfide (DMS)-cloud albedo. Feedbacks that involve clouds are particularly relevant to the Arctic because clouds influence the physical processes most important for the warming of the Arctic and the melting of sea ice. Clouds remain one of the largest uncertainties in climate modeling. Because of their relatively high reflectivity (albedo), similar to snow- and ice-covered surfaces, clouds may exert a net cooling effect as sea ice vanishes, at least during months of significant solar radiation. Cloud properties such as albedo, extent, and duration are determined in large part by cloud condensation nuclei (CCN). The source of CCN over the summertime Arctic is nucleated particles of marine biogenic origin that grow to CCN size with the aid of aerosol precursor gases, predominately DMS.

ARCTIC SYSTEM MODELING VIGNETTES

Biological release of DMS relates back to the productivity of arctic oceans and interconnects the sulfur

cycle to other major element cycles (carbon, nitrogen, iron) with their own potential feedbacks on climate. An ASM would provide the frame-

work to link all the components in the feedback loops. It would be a means for evaluating the signs, quantifying the strengths, and measuring the uncertainties.

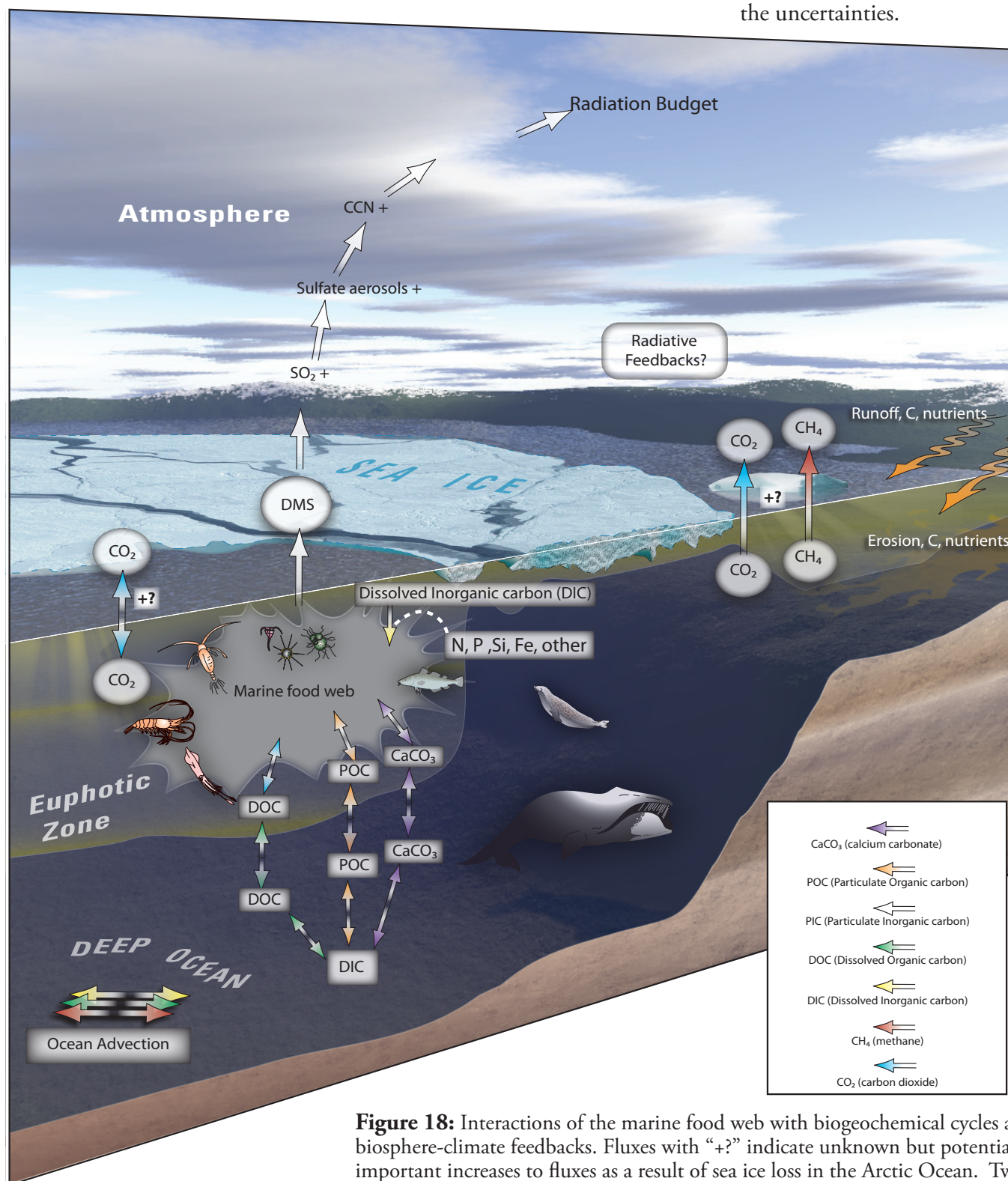


Figure 18: Interactions of the marine food web with biogeochemical cycles and biosphere-climate feedbacks. Fluxes with “+?” indicate unknown but potentially important increases to fluxes as a result of sea ice loss in the Arctic Ocean. Two-way arrows indicate exchanges in both directions, and “+” indicates potential increases in atmospheric components that influence the Earth’s radiation budget.

7. Short-Term Impacts of Permafrost Degradation on Climate

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Vladimir Romanovsky—University of Alaska Fairbanks

Introduction

The response of the arctic land surface to changing climate is dynamically coupled with the evolution of permafrost, which is intimately linked to the local surface energy balance. The local surface energy balance, in turn, is a function of soil hydrology and vegetation, which is strongly controlled by permafrost features such as active layer thickness, ice content, and its spatial distribution. The complex interrelationships between permafrost, hydrology, vegetation, and climate continue to confound our ability not only to project when and where permafrost will degrade but also, more generally, to understand how permafrost degradation and associated land surface change affect climate. A fundamental unresolved question is precisely what role permafrost plays in maintaining present arctic climate. Furthermore, how will permafrost thaw alter arctic hydrology and, more broadly, the climate system? Is permafrost a passive component of the physical system, acting predominantly as an integrator of long-term variations in weather and climate, or does it also play a more active role in shaping local climate and the regional response to climate change? Addressing these questions requires a coupled model that can realistically simulate both the varied land surface response to permafrost degradation and the atmospheric response to changing land state.

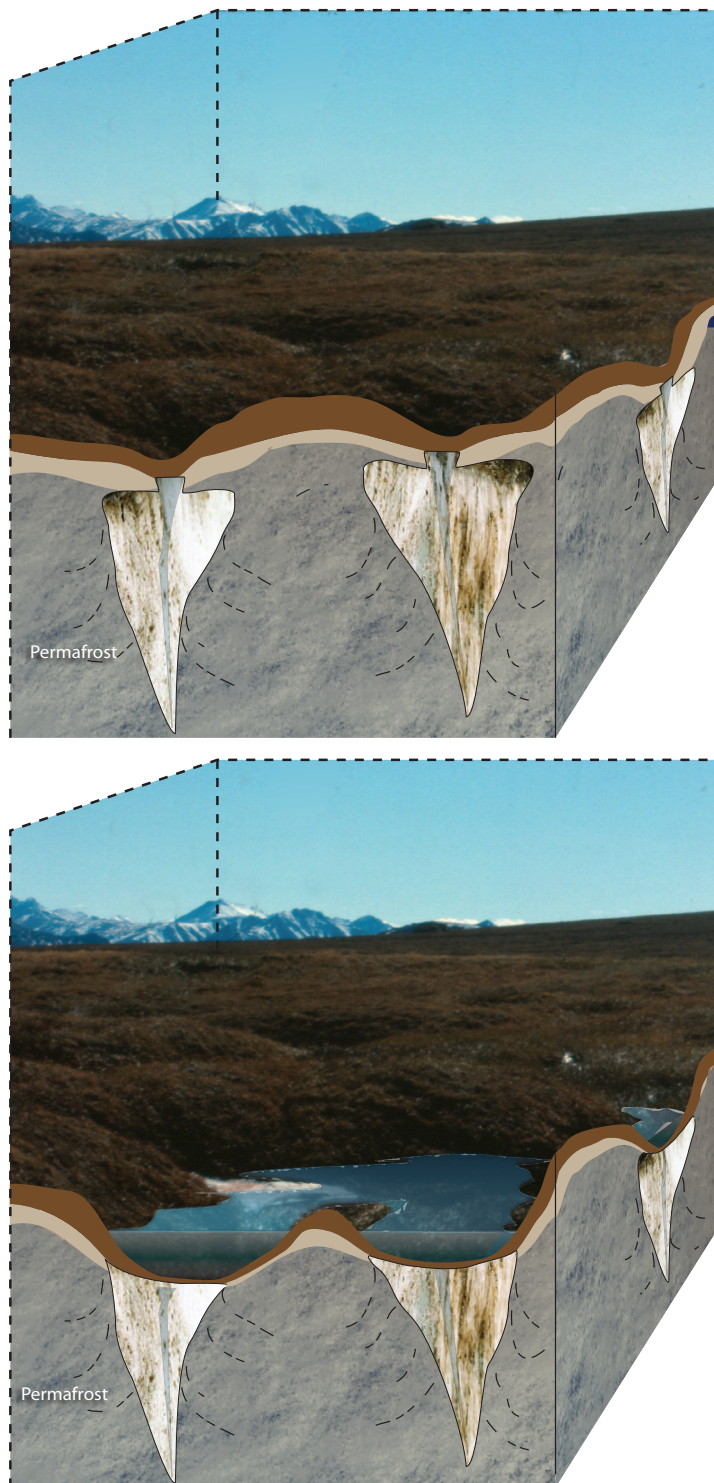


Figure 19: Massive ice, often in the form of wedges or veins, may occupy 30–50% of the total permafrost volume, and sometimes more (Kanevskiy et al., 2008). Thermokarst topography forms as ice-rich permafrost thaws and the ground surface subsides into the resulting voids. The important and dynamic processes involved in thermokarst include thaw, ponding, surface and subsurface drainage, surface subsidence, and related erosion. These processes are capable of rapid and extensive modification of the landscape.

The Role of Permafrost in the Climate System

In general, most permafrost projection modeling studies have focused on the one-way response of permafrost to climate change by forcing a permafrost model with climate change projections obtained from a Global Climate Model (Anisimov et al., 1997; Romanovsky et al., 2007; Marchenko et al., 2008). Due to the complexities of vegetation and surface and subsurface hydrological responses to warming, the one-way approach will continue to be a challenging project. It will benefit from the high resolution afforded by a regional model that can better capture surface heterogeneities such as topography, aspect, disturbance, and spatial variations in snow cover, snow depth, organic layer thickness, and vegetation that will dictate the soil temperature response to warming. However, one-way modeling cannot provide insight into two-way permafrost-climate interactions and related positive and negative feedbacks operating in the real system that could amplify or mitigate climate change.

How might permafrost and its degradation feed back onto climate? The primary pathway is via the influence that permafrost conditions exert on soil hydrology and vegetation. Soil hydrology and vegetation together impart a strong influence on the surface water, energy, and momentum fluxes that constitute the bottom boundary condition for the atmosphere. Broadly speaking, thick continuous permafrost zones are characterized by moist soil

and a shallow active layer, while discontinuous permafrost zones are characterized by drier and more spatially heterogeneous soil moisture conditions and deeper active layers (Figure 19; see White et al., 2007 for review). Active layer thickness and soil moisture are strong determinants of vegetation distribution. Warming and degradation of permafrost in continuous permafrost zones will lead to an increase in the active layer depth and a possible shift from prone shrub tundra to more erect shrub tundra. The erect shrub tundra tends to be darker (lower albedo), leading to enhanced solar absorption and more surface energy available for heating of both the soil and the overlying atmosphere. Degradation in discontinuous zones may initiate a shift from wetter toward drier soil conditions with corresponding shifts in vegetation from, for example, boreal forest to grassland. However, grasslands have a higher albedo than forests and therefore this shift may lead to less available surface energy. Grasslands also transpire less, which in combination with drier soils will shift the partitioning of sensible (SH) and latent heat (LH) fluxes (e.g., Bowen ratio = SH/LH) toward a higher Bowen ratio. A higher Bowen ratio equates to a deeper and drier boundary layer. Since boundary layer depth and low cloud formation tend to be inversely related, a deeper and drier boundary may lead to fewer low clouds and more solar insulation. For this scenario (e.g., conversion of boreal forest to grassland) the magnitude and sign of the

atmospheric feedback will depend on the extent to which the boundary layer and cloud responses (and other related atmospheric circulation or precipitation responses) offset the albedo change.

An additional pathway by which permafrost, especially ice-rich permafrost, can influence climate is its effect on the surface energy budget through its role as a large heat sink. During thaw, the ground accumulates a lot of heat to melt the permafrost ice. To what extent does this act as a negative feedback on surface warming? More generally, how much does the presence of deep cold permafrost suppress summer air temperatures? And once permafrost in a given region has thawed completely, will the reduction of the heat sink result in more substantial surface warming?

Additional production of greenhouse gases from thawing permafrost is another potentially strong positive feedback between climate change and permafrost dynamics. When permafrost thaws, a rapid decomposition of organic matter sequestered for many hundreds or thousands of years occurs, emitting carbon dioxide and/or methane into the atmosphere. Further permafrost degradation and formation of talik, a layer that will not freeze during the winter, will amplify these changes. A talik will appear above the permafrost and allow microbial activity to continue during the winter. Thus, permafrost thawing acts as a positive feedback to climate warming, which is projected to intensify with further permafrost degradation in the future.

8. Forecasting Environmental Resilience of Arctic Freshwater Resources: Using Agent-Based Modeling to Understand Social Ecological Systems

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Mark Altaweel—University of Chicago
Computation Institute

Introduction

In recent years, a focused effort has been underway to develop a robust architecture for modeling coupled social ecological systems in the Arctic. Social-ecological theory, also referred to as human ecodynamics (McGlade, 1995; Kirch, 2005), posits that the interactions of societies and their ecosystems over time result in cultural and environmental changes at varied spatial scales. Communities consist of many individuals who make choices based on their personal values, perceptions, and circumstances. In the case of water resource-related decision-making, people use information about their resources such as how they are changing and what the potential responses to these changes are (Alessa et al., 2008a). Possible responses include migration or coping with changed social-hydrological realities. Values and perceptions can change as a result of information received about water resources. Community-scale decisions depend on the dominant suite of values, perceptions, and norms in addition to the means and opportunities available (e.g., options to extract minerals, harvest salmon, build a hydroelectric dam, etc.) and the socioeconomic/political context in which those decisions are made. Individual decisions can affect water resources, resulting in feedbacks for the human-hydrological system that make it more or less resilient and, hence, more or less sustainable over longer periods of

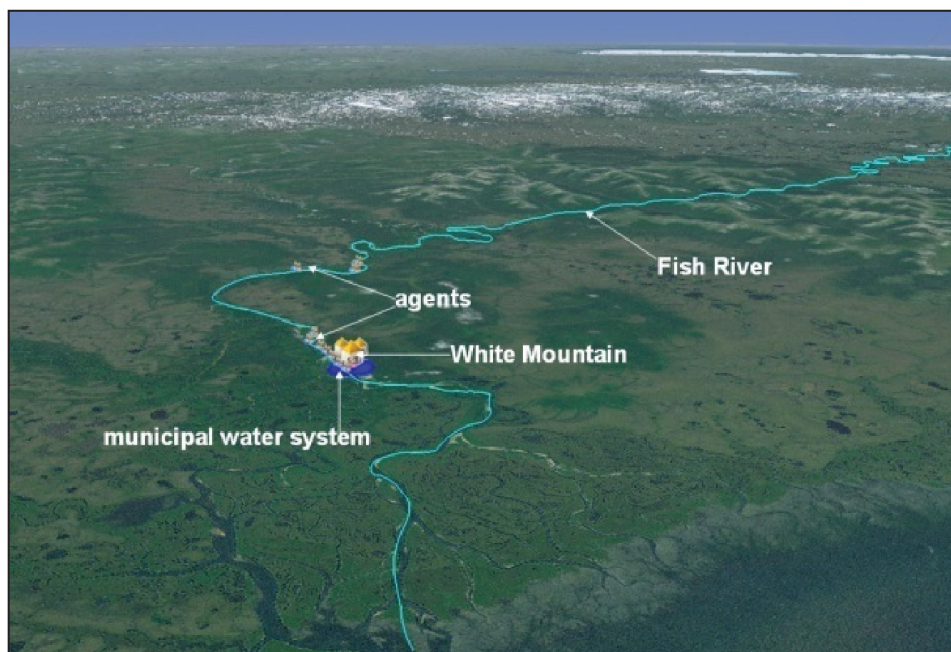


Figure 20: Image showing a modeling scenario with the village of White Mountain, Alaska, agents (individuals collecting water), the municipal water system, and the predominant natural water source (Fish River) visualized in a 3D environment.

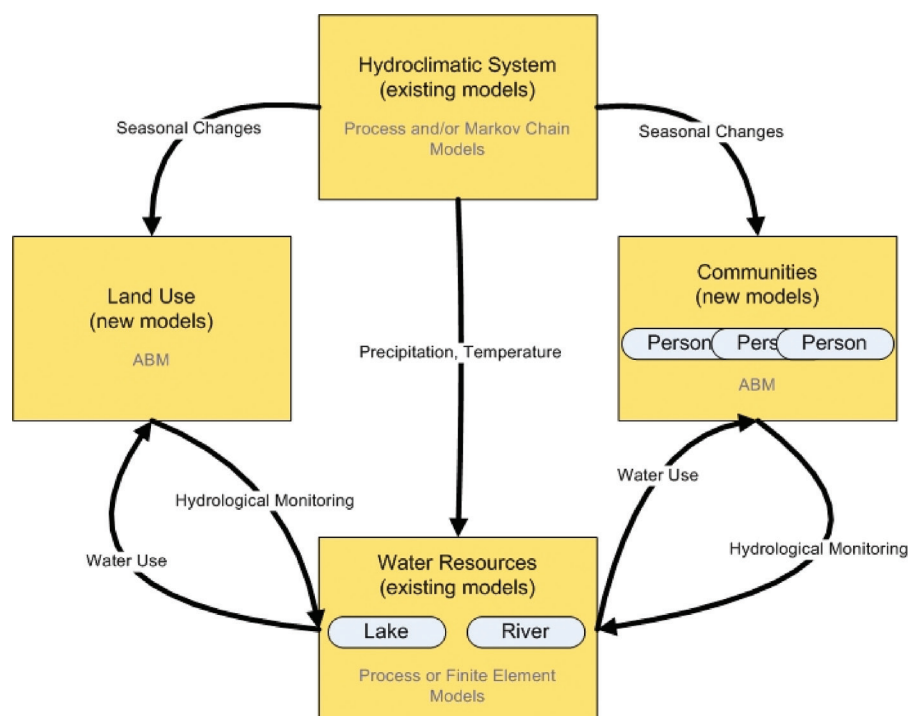


Figure 21: An Arctic System Model must couple social and biophysical components and processes. Social models implement modeling techniques that include agent-based modeling (ABM) methodologies, and social units include individuals, communities, and industries; all of these components have a heavy dependence on water use.

time (Alessa et al., 2007). The Arctic provides a good laboratory in which to examine questions concerning the dynamics of perceptions of water and the feedbacks with respect to water resources, including hydrology and permafrost.

Understanding the resilience of freshwater resources is one of the most challenging and complex issues facing communities across the globe (Postel, 2000). United Nations Secretary General Ban Ki-moon cited the looming crisis of worldwide water supply as the UN's top global agenda for 2008 because of the relationship of water to socio-political unrest in many areas of the world. For the arctic region, in the last 50 years accelerations in a wide range of hydrological changes have been detected through physical measurement (Overpeck et al., 1997). These observations form a case that the arctic hydrological system may rapidly be entering a state unseen in historic times (Magnuson et al., 2000; Serreze et al., 2000; Holland et al., 2007)—a state that will have significant implications for the inhabitants of the region (ACIA, 2005). Discontinuous permafrost, above which most arctic communities are located, shows a distinct thawing trend and is correlated to changes in both groundwater and surface hydrology (Osterkamp and Romanosvsky, 1999; Hinzman et al., 2005). Such changes potentially have a wide range of effects on water resources (Quinn et al., 1997; Pollard, 2005; Vörösmarty et al., 2000) and may be perceived by residents differently, resulting in a variety of consequences including whether or not a response is warranted (Alessa et al., 2007).

Resilience and Vulnerability in Freshwater Systems: Climate Change and Land Use

In addition, the Arctic is experiencing transformation as a consequence of land use decisions (resource development) and rapid rates of climate change, particularly warming. Land use change and conversion, such as mining activities, can alter high-latitude hydrology arguably more rapidly than climate change (Forbes, 1999). This relatively fast driver interacts with the relatively slower driver of warming-induced changes in regional precipitation to potentially increase flood risks in some areas and drought in others (Eshleman, 2004). The effects of land use and climate change on water supplies in the Arctic have the potential to severely impact the cultures, lifestyles, and resource use patterns of communities residing there. Industrialization has brought rapid increases in rates of change of social, economic, and environmental systems throughout the Arctic. The thawing of discontinuous permafrost, which in many cases holds water close to the surface, has resulted in the draining of lakes throughout the North (Yoshikawa and Hinzman, 2003). Over the past four years we have talked with residents (Alessa et al. 2008a, 2008b) who provide highly detailed accounts of a drying Arctic:

“The creeks are lower than they used to be, you can't boat far up the river like before, the rain doesn't always come in time for the berries now.”—*64-year-old Seward Peninsula elder.*

Similarly, changes in albedo associated with road building can occur quickly and be cumulative

(Hinzman et al., 2005). These finer-scale changes may interact with broader scale changes such as the northward migration of woody shrubs that could mitigate erosion effects associated with tundra. In essence, hydrological dynamics are primarily influenced by faster changing fine-scale and secondarily by slower broad-scale variables. However, what is not clear is how human behaviors feed back to influence such changes.

Models of human water use that integrate with hydrological systems do not exist for the Arctic. Thus, a new generation of modeling efforts, focused around agent-based models, is underway to aid our understanding of the effects of water perception, valuation, and use by individuals and social units. These provide the first opportunity to understand the complex human-hydrological system as a truly coupled social-ecological system by using both biophysical and socio-cultural data (Figures 20 and 21). It assists our understanding of the consequences of long-term freshwater changes in arctic social-ecological systems by allowing models that address these systems to interact over varied spatial and temporal scales.

Part of the modeling challenge is that decision making and its consequences are inherently spatially bound. We need to understand the relative spatial distribution of social values and water resources in order to understand the consequences of water use decisions. In order to accomplish this, previous work established the social-ecological hotspots mapping methodology (Alessa et al., 2007) that can be applied in a system modeling framework.

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ACRONYMS AND ABBREVIATIONS

ACIA	Arctic Climate Impact Assessment
AO	Arctic Oscillation
AOGCM	Atmosphere-Ocean General Circulation Model
AOMIP	Arctic Ocean Model Inter-comparison Project
AON	Arctic Observing Network
ARCMIP	Arctic Regional Climate Model Inter-comparison Project
AR4	IPCC's fourth assessment report
ASCOS	Arctic Summer Cloud Ocean Study
ASM	Arctic System Model
CARCMIP	Coupled Ocean-Ice-Atmosphere-Land Model Inter-comparison Project
CCN	Cloud Condensation Nuclei
CCSM	Community Climate System Model
CIRES	Cooperative Institute for Research in Environmental Sciences
DAMOCLES	Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies
DIC	Dissolved Inorganic carbon
DMS	Dimethylsulfide
DOC	Dissolved Organic carbon
ENSEMBLES	ENSEMBLE-based Predictions of Climate Changes and their Impacts
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GLIMPSE	Global Implications of Arctic Climate Processes and Feedbacks
GODAE	Global Ocean Data Assimilation Experiment
HOME	Hybrid Ocean Modeling Environment
IARC	International Arctic Research Center
IDAAS	Integrative Data Assimilation for the Arctic System
IC	Ice Caps
IPCC	Intergovernmental Panel on Climate Change
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
LANL	Los Alamos National Laboratory
LH	Latent Heat
MG	Mountain Glaciers
MIZ	Marginal Ice Zones
MM5	Mesoscale Model 5
NAM	Northern Hemisphere Annular Mode (see also AO)
NAO	North Atlantic Oscillation
NCAR	National Center for Atmospheric Research
NOAA	National Oceanographic and Atmospheric Administration
NSIDC	National Snow and Ice Data Center
S4D	SEARCH for DAMOCLES
SEARCH	Study of Environmental Arctic Change
SH	Sensible Heat
SSC	CCSM Scientific Steering Committee
WRF	Weather Research and Forecasting model



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This science plan is a result of three workshops held during and immediately after the International Polar Year 2007–2009:

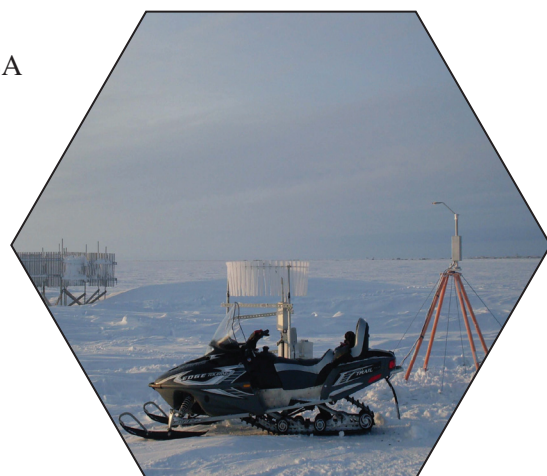
1. Arctic System Modeling Workshop I: Preliminary Ideas. Convened at the International Arctic Research Center, University of Alaska Fairbanks, Alaska, August 6–7, 2007, 49 participants (http://www.iarc.uaf.edu/workshops/2007/arctic_system_model_07).
2. Arctic System Modeling Workshop II: Science Planning. Convened at the National Center for Atmospheric Research, Colorado, May 19–21, 2008, 46 participants (http://www.iarc.uaf.edu/workshops/2008/arctic_system_model_08).
3. Arctic System Modeling Workshop III: International Collaboration in Arctic System Modeling. Convened at the University of Quebec at Montreal, Quebec, July 16–17, 2009, 67 participants (http://www.iarc.uaf.edu/workshops/2009/arctic_system_model_09).

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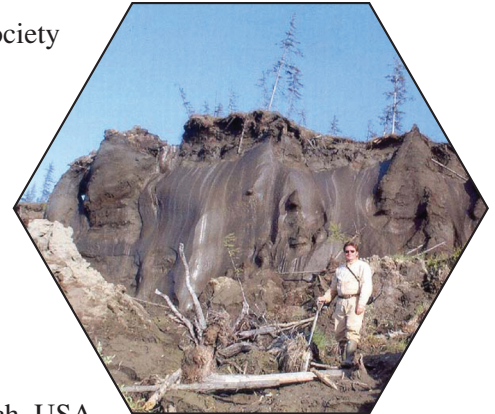


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Acknowledgments

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